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AD-A280 259



Technical Report CERC-94-7

April 1994



Los Angeles and Long Beach Harbors, Model Enhancement Program, Effects of Wind on Circulation in Los Angeles-Long Beach Harbors

by William C. Seabergh, S. Rao Vemulakonda,
Lucia W. Chou, David J. Mark

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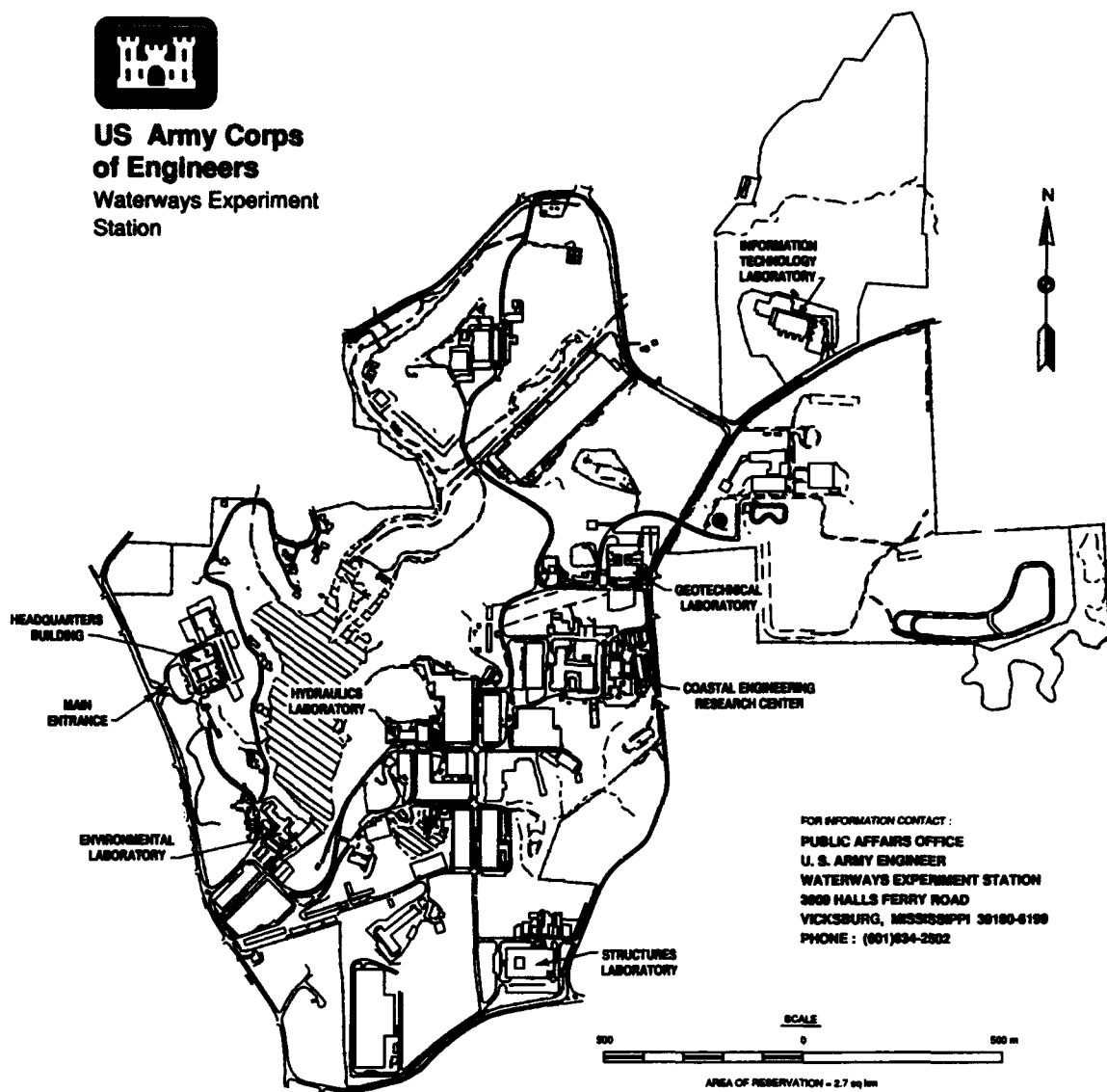
Prepared for U.S. Army Engineer District, Los Angeles
Post Office Box 2711
Los Angeles, CA 90053-2325

Port of Los Angeles
San Pedro, CA 90733-0151

and Port of Long Beach
Long Beach, CA 90801-0570



**US Army Corps
of Engineers**
Waterways Experiment
Station



Waterways Experiment Station Cataloging-in-Publication Data

Los Angeles and Long Beach Harbors, Model Enhancement Program, effects of wind on circulation in Los Angeles-Long Beach Harbors / by William C. Seabergh ... [et al.] ; prepared for U.S. Army Engineer District, Los Angeles, Port of Los Angeles, and Port of Long Beach.

217 p. : ill. ; 28 cm. — (Technical report ; CERC-94-7)

Includes bibliographic references.

1. Hydrodynamics — Mathematical models. 2. Harbors — California — Hydrodynamics. 3. Wind waves. 4. Ocean circulation. I. Seabergh, William C. II. United States. Army. Corps of Engineers. Los Angeles District. III. WORLDPORT LA. IV. Port of Long Beach. V. U.S. Army Engineer Waterways Experiment Station. VI. Title. VII. Series: Technical report (U.S. Army Engineer Waterways Experiment Station) ; CERC-94-7.
TA7 W34 no.CERC-94-7

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Preface

This report was prepared by the Coastal Engineering Research Center (CERC) at the U.S. Army Engineer Waterways Experiment Station (WES) and is a product of the Los Angeles and Long Beach Harbors Model Enhancement (HME) Program. The HME Program has been conducted jointly by the Ports of Los Angeles and Long Beach (LA/LB); the U.S. Army Engineer District, Los Angeles (SPL); and WES. The purpose of the HME Program has been to provide state-of-the-art engineering tools to aid in port development. In response to the expansion of oceanborne world commerce, the Ports of LA/LB are conducting planning studies for harbor development in coordination with SPL. Ports are a natural resource, and enhanced port capacity is vital to the Nation's economic well-being. In a feasibility study being conducted by SPL, the Ports of LA/LB are proposing a well-defined and necessary expansion to accommodate needs predicted for the near future. The Corps of Engineers will be charged with responsibility for providing deeper channels and determining effects of this construction on the local environment. This includes changes in harbor resonance caused by expansion and channel deepening.

The investigation was conducted during the period January 1990 through September 1991 by personnel of the Wave Processes Branch (WPB), Wave Dynamics Division (WDD), and the Research Division (RD), CERC. WPB was included in the study by Mr. William C. Seabergh, under the direct supervision of Mr. Douglas Outlaw, former Chief, WPB, and Mr. Dennis G. Markle, current Chief, WPB, and Mr. C. E. Chatham, Chief, WDD. RD personnel involved in the study were Dr. S. Rao Vemulakonda and Mr. David J. Mark, under the direct supervision of Dr. Martin C. Miller, Chief, Coastal Oceanography Branch, and Ms. Lucia W. Chou, under the direct supervision of Mr. Bruce A. Ebersole, Chief, Coastal Processes Branch. Mr. H. Lee Butler was Chief, RD. Mr. Seabergh and Dr. Vemulakonda, with the assistance of Mr. Mark and Ms. Chou, prepared the report. Ms. Debbie Fulcher, WPB, assisted in preparation of the final report. Overall CERC management of the HME Program was furnished by Messrs. Outlaw and Seabergh, and this study was conducted under the general supervision of Dr. James R. Houston, Director, CERC, and Mr. Charles C. Calhoun, Jr., Assistant Director, CERC.

During the course of the study, significant liaison was maintained between WES, SPL, and the Ports. Mr. Dan Muslin, followed by Mr. Angel P. Fuertes, Mr. Mike Piszker, and then Ms. Jane Grandon were SPL points of contact. Mr. John Warwar, Mr. Dick Wittkop, and Ms. Lillian Kawasaki, Port of Los Angeles, and Mr. Michael Burke, followed by Mr. Angel Fuertes and Dr. Geraldine Knatz, Port of Long Beach, were Ports of LA/LB points of contact and provided invaluable assistance.

Dr. Robert W. Whalin was Director of WES at the time of publication of this report. COL Bruce K. Howard, EN, was Commander.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.028317	cubic meters
degrees (angle)	0.01745329	radians
feet	0.3048	meters
miles (US statute)	1.6093	kilometers
miles per hour (mph)	0.4470	meters per second
square miles	2.590	square kilometers

1 Introduction

Background

Los Angeles and Long Beach Harbors (Figure 1) are located adjacent to each other in San Pedro Bay on the southern California coast. They share a common breakwater system. Ocean waters circulate into, out of, and between both harbors due to the action of tides and wind. Angel's Gate and Queen's Gate are the two major entrances to the harbors, in addition to an opening at the eastern end. As these ports respond to the expansion of oceanborne world commerce and propose plans to accommodate future needs (including deeper channels and landfills), environmental impacts (including impacts on circulation) must be examined. Approaches to examine plan impacts include modeling, and in the cases of Los Angeles and Long Beach Harbors, there have been several numerical model studies of tidal circulation (Chiang and Lee 1982, Seabergh and Outlaw 1984, Seabergh 1985). Most of the previous numerical circulation studies were performed using depth-averaged models such as WIFM (Butler 1980) and using only tides for forcing. Recently, the ports, together with the U.S. Army Engineer District, Los Angeles and the U.S. Army Engineer Waterways Experiment Station (WES), embarked on a Harbors Model Enhancement (HME) Program. The program is outlined in Table 1. As a part of HME, the Coastal Engineering Research Center (CERC) of WES calibrated and verified a three-dimensional (3D) hydrodynamic model with field data. The model was forced with tides and wind, using measured surface elevations at the offshore boundary. The results of these efforts are described in Vemulakonda and Butler (1989), and CERC (1990). As a follow-up to this work, the effects of different winds on circulation in the harbors were examined (using the same 3D numerical hydrodynamic model and the same 1987 harbor configuration). This report describes the results of these model simulations.

Table 1
Tasks of the Harbors Model Enhancement Program
A. Harbor Resonance and Ship Motion
Wave Data Acquisition
Wave Data Analysis
Harbor Resonance Analysis
Ship Motion Data Collection and Analysis
Ship Motion Model Development, Calibration and Verification
Improved Physical Model Harbor Resonance
B. Tidal Circulation
Data Acquisition
Circulation Transport Modeling
Water Quality Evaluation Model
Wind-Driven Circulation Analysis
C. Project Management
D. SPL Coordination

Objective

This report is the second in Task B.4, "Wind-Driven Circulation Analysis," of the Model Enhancement Program. The first report (Smith 1989) examined a prototype data set gathered in the harbors by the National Oceanic and Atmospheric Administration in the summer of 1983. That data set consisted of tidal current measurements, tidal elevations, and local wind measurements. The present report will summarize winds over the harbors and examine, with the aid of a calibrated numerical model, the effects of various wind conditions on circulation throughout the harbors.

Chapter 2 discusses typical wind conditions, Chapter 3 describes selection of test conditions, Chapter 4 presents the numerical hydrodynamic model applied in this study, Chapter 5 examines tests and analysis performed, and Chapter 6 presents conclusions. For convenience, the abbreviations LA and LB will be used throughout this report to indicate Los Angeles and Long Beach, respectively.

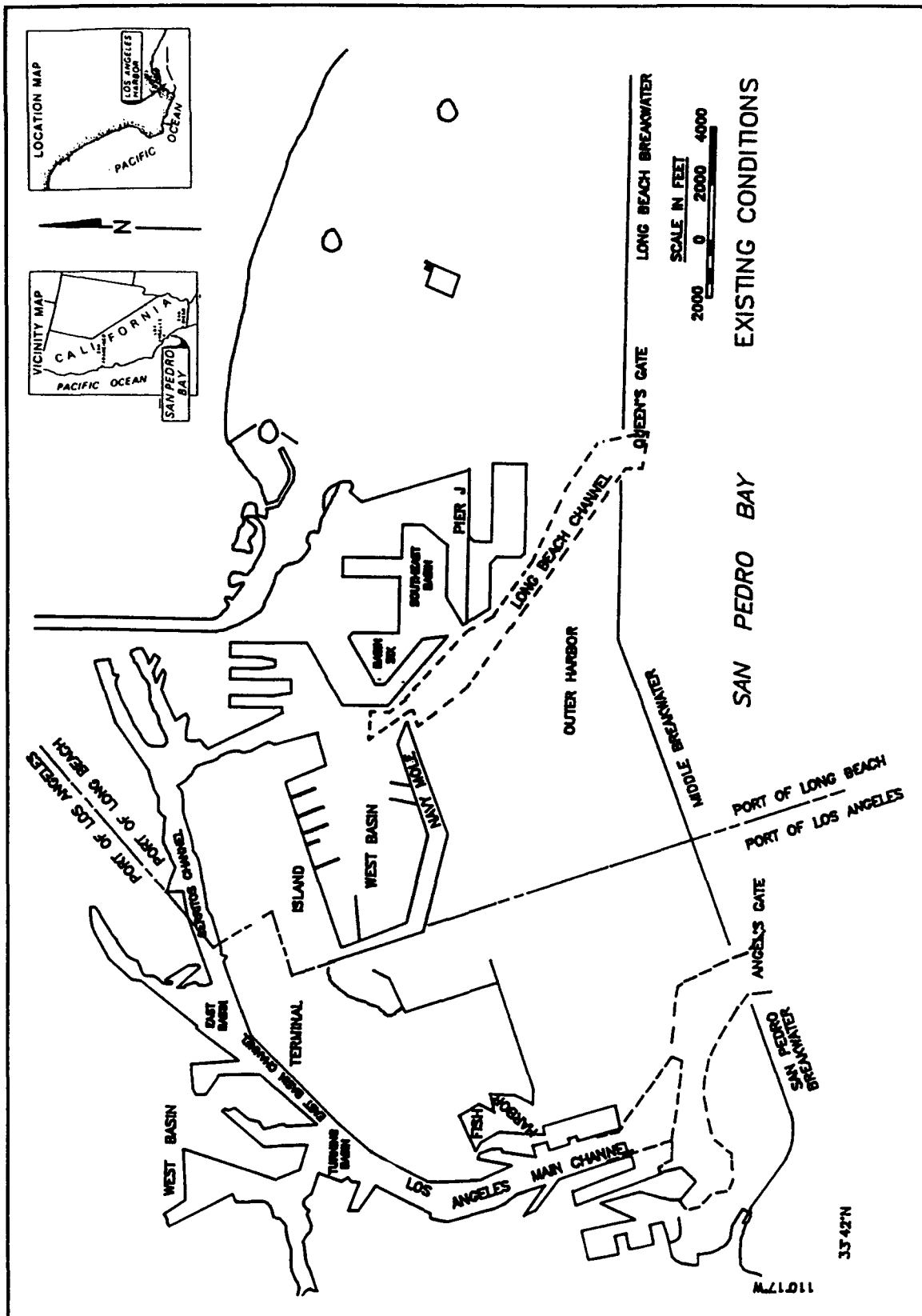


Figure 1. Los Angeles and Long Beach Harbors layout

2 Winds Over the Harbors

Typical Conditions

The basic feature of the wind pattern for the harbors is a land-sea breeze regime caused primarily by differential heating of water and land. In summer, this pattern is characterized by onshore winds from west to southwest during the day, peaking at about 20 mph.¹ Onshore wind can persist throughout the night. From Figure 1 it can be seen that these onshore winds move along the wider axis of the outer harbor of both ports, i.e., from a westerly direction. Figure 2 shows onshore winds predominating from 1-19 July 1988. The direction shown is the direction from which wind is blowing, measured clockwise from true north. The 22 June - 20 July 1988 wind rose (Figure 3) illustrates this onshore predominance. Figure 3 shows a cumulative plot of measurements near Angel's Gate indicating the predominant wind direction from 240-260 deg. Because wind measurements shown in Figures 2 and 3 were collected on the San Pedro breakwater, they are representative of winds over the harbors' water surface. Typically the daily duration of onshore winds reduces as daily temperatures reduce in cooler seasons. The 16 October - 13 November 1985 wind rose (Figure 3) shows that even in fall/winter the onshore southwest winds are still an important component of the wind pattern. However, strong winds from the southeast and north-northwest, associated with approaching and passing frontal conditions, respectively, become important with regard to winter wind patterns and are the dominant winds in the October - November wind rose. Northwest winds are intensified for several days after passage of a front, with sustained winds of up to 25 mph being common. "Hurricane Gulch" is a commonly used term to describe the stronger westerly winds from Cabrillo to Seal Beach, due to the northwest winds whipping around Palos Verdes².

¹ A table of factors for converting non-SI units of measurement to SI units is presented on page vi.

² Personal Communication, August 1993, Jane Grandon, Civil Engineer, U.S. Army Engineer District, Los Angeles, Los Angeles, CA.

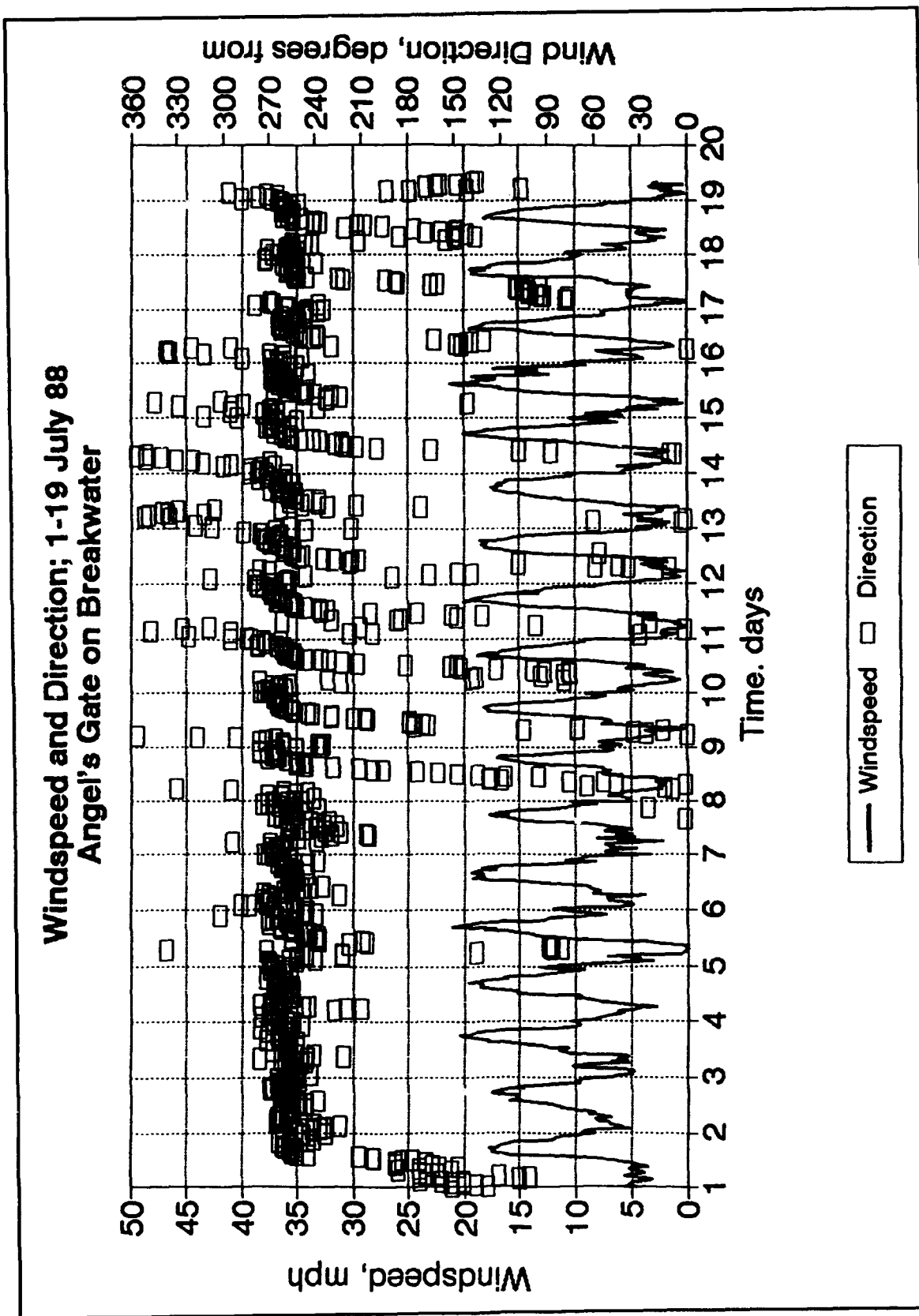


Figure 2. Wind speed and direction at Angel's Gate on San Pedro breakwater, 1-19 July 1988

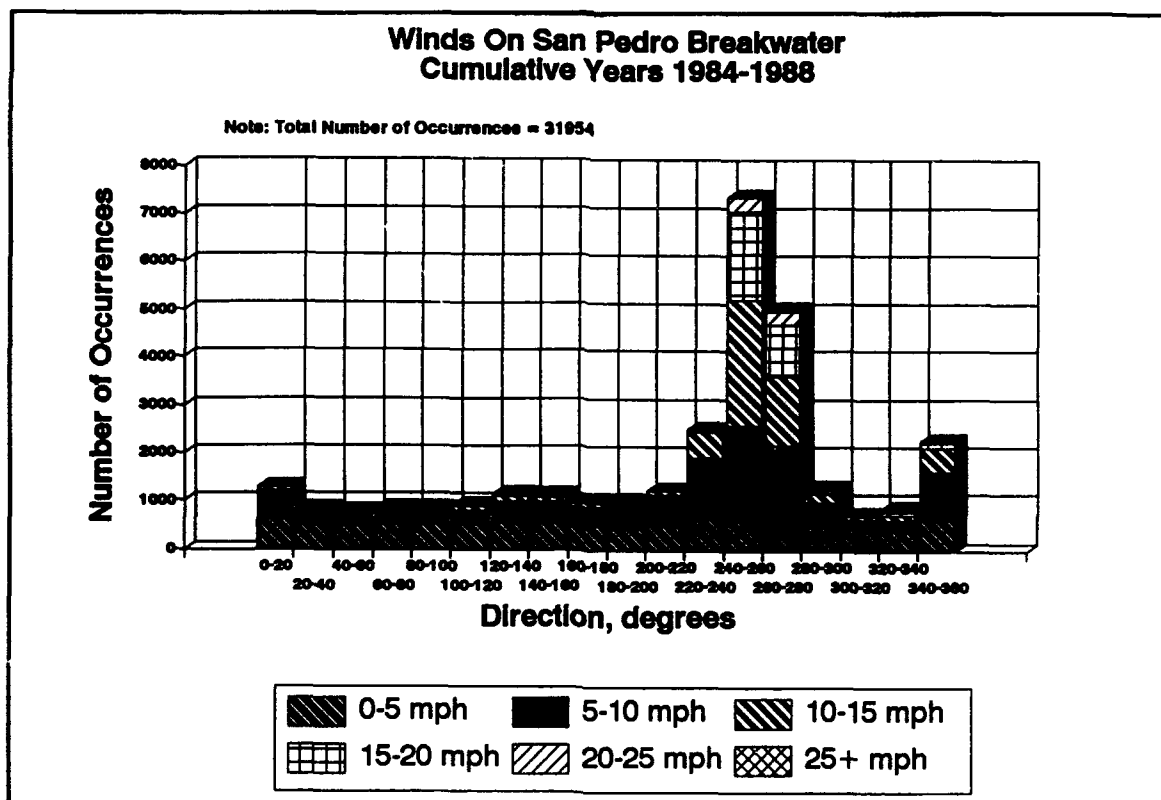
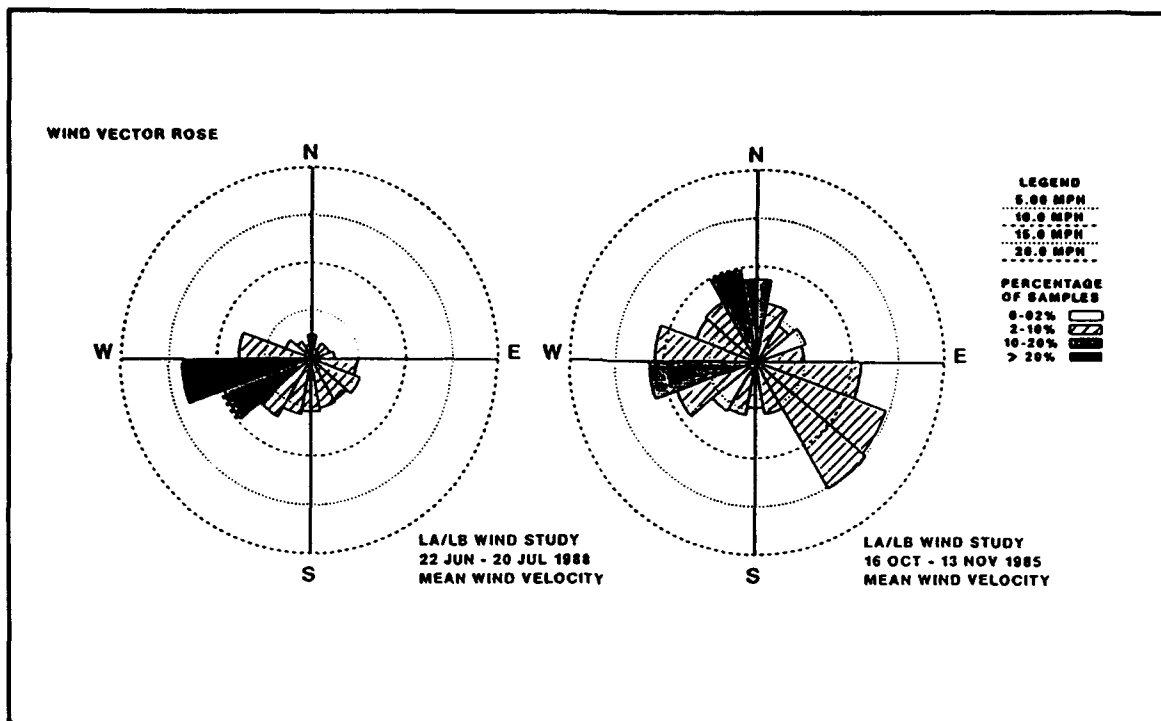


Figure 3. Seasonal wind roses and cumulative wind speed directional distribution measured at San Pedro breakwater near Angel's Gate

Wind Data Examined

At the time of this study, there was not a truly comprehensive meteorological station being operated in the harbors, so that data sources were sometimes difficult to access, or data were in a format that was difficult to handle (e.g., strip chart records). Wind data examined included those from the Headquarters buildings of the Port of Los Angeles (POLA) and the Port of Long Beach (POLB), the Los Angeles Pilot Station and the Los Angeles breakwater, the Los Angeles International Airport, and the Long Beach Airport, as shown in Figures 4 and 5. Data from the airports are comprehensive but may not be truly representative of the wind conditions over the harbors as Figure 6 shows, which compares data at the breakwater and the Long Beach Airport. Figure 7 compares monthly average wind conditions at the Los Angeles and Long Beach Airports, which indicates lower average winds at Long Beach Airport, 5 miles inland. The Los Angeles Airport is adjacent to the ocean, but differences in wind direction exist between this airport and the harbors. This is due to change in shoreline orientation and existence of hilly terrain just west of the harbors (as can be noted in Figure 4), which are important factors affecting the daily shoreward winds.

Data gathered by WES on the San Pedro breakwater near Angel's Gate from July 1984 to November 1988 are probably the most representative of winds directly over harbor waters. The monthly summary roses are included as Plates 1 - 26. Bar charts summarizing the data by months are included in Appendix A. These data do not cover the entire period from July 1984 to November 1988, due to occasional equipment problems and logistical problems associated with funding constraints; however, they appear to represent seasonal variations in patterns. The anemometer was 30 ft above water and sampled data every one-half hour. Wind conditions selected for model testing described in this report were obtained from this data set.

An analysis was performed to examine strong winds and gustiness using strip chart records of wind speed and direction recorded at the Los Angeles Harbor Pilots' Station (Figure 4). Data from 27 September 1976 through 2 February 1983 were examined, and for maximum hourly gusts (where a gust is defined here as a rapid rise - a minute or less - in wind speed and a similar decline), the gust direction and the average hourly wind speed and direction were determined. A total of 438 events occurred, with most of the lower values reflecting afternoon onshore winds from the west and southwest. The higher wind speeds and gusts were from the east and southeast, associated with approaching fronts. The upper portion of Figure 8 shows maximum hourly gusts during high gust conditions (typically greater than 20 mph) versus average hourly wind speed. A linear relation between gust strength, G (in mph), as defined above, and average hourly wind speed, W (in mph), was determined to be

$$G = 1.1 W + 6.1$$

This type of information, though not critical to effects on circulation in the harbors, may be important to ship handling and the roll motion of moored

ships. It does, however, indicate that stronger, more turbulent, wind events approach from the east to southeast direction, as noted in the lower portion of Figure 8.

Santa Ana winds describe the high sustained winds that can occur when a strong high pressure system is located over the western United States, typically centered on Nevada and Utah. This occurs after a front has moved inland through northern California and Nevada followed by a Pacific high. Generally winds approach from the northeast, but they can be locally affected by topography. Santa Anas typically occur from November through January. Favored courses of Santa Ana winds are shown in Figure 9, a Weather Service sketch (Kurtz 1977). Santa Ana winds of 64 mph did significant damage to the harbors in 1933 (Marine Advisers, Inc. 1965). Figure 10 shows winds with peak velocities of 24 mph that occurred on the breakwater when Santa Ana winds were 80 mph inland. These winds approached the harbors from the northeast, or 45 deg.

Winds due to tropical storms or hurricanes have reached the harbors only a few times since weather records have been kept. Typically these form near the equator south of the Gulf of California in July, August, and September, moving west to northwest. Usually high pressure centers north of the hurricane keep it moving away from the coast of Mexico and Southern California. In 1921, 1929, and 1939 (in September in each case) hurricanes advanced to the Southern California coast, with only the 1939 hurricane reaching San Pedro Bay, causing significant damage in the vicinity of the harbors.

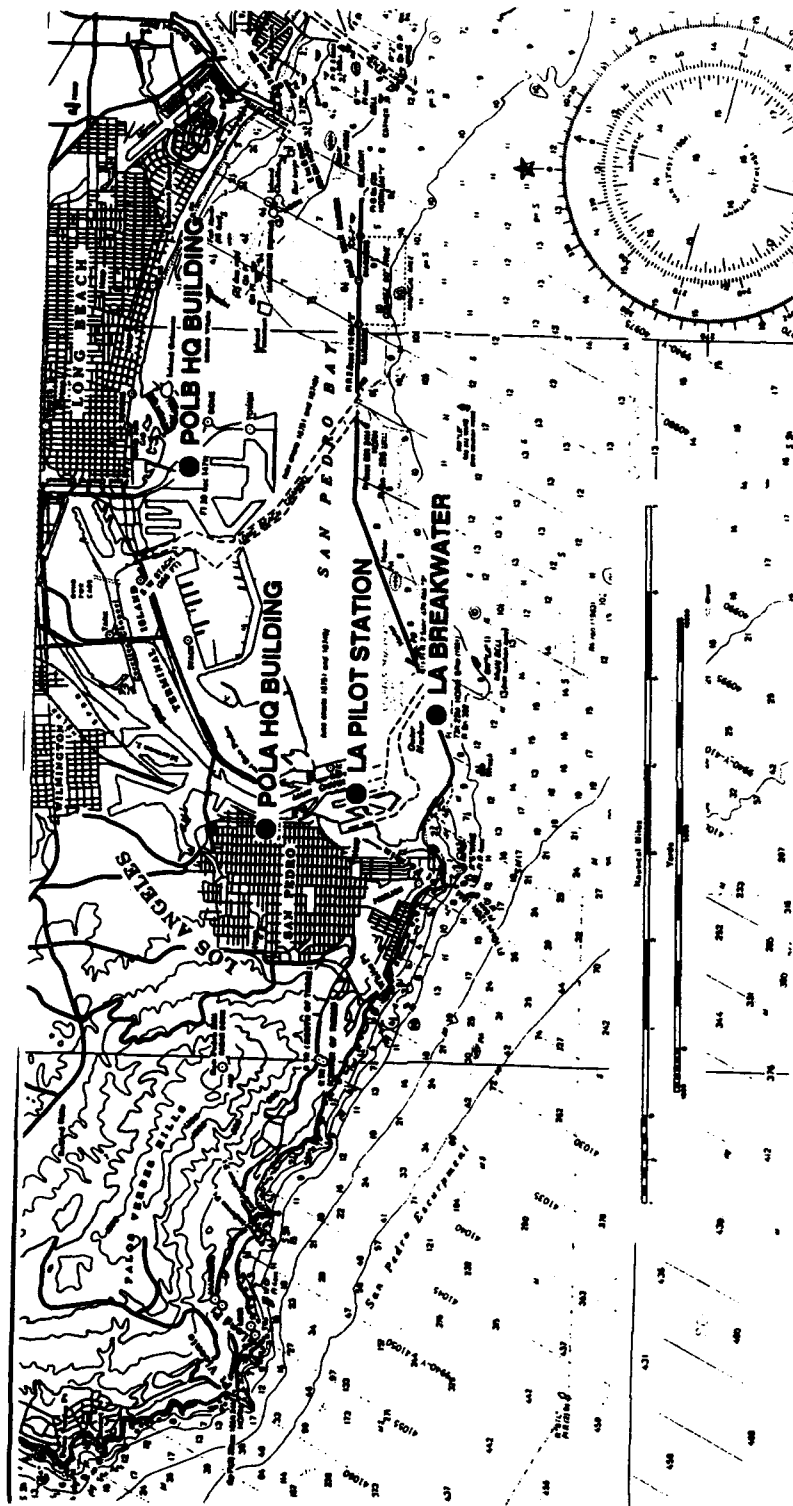


Figure 4. Locations of wind measurements and local terrain



Figure 5. Airport wind measurement location

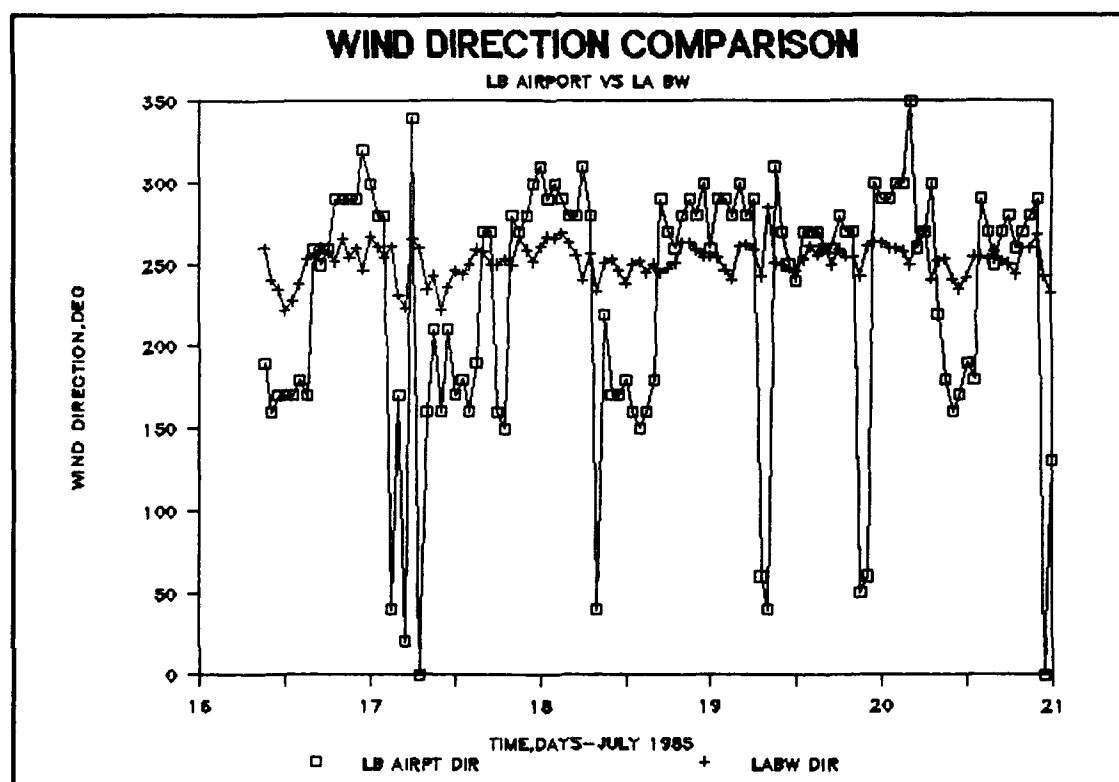
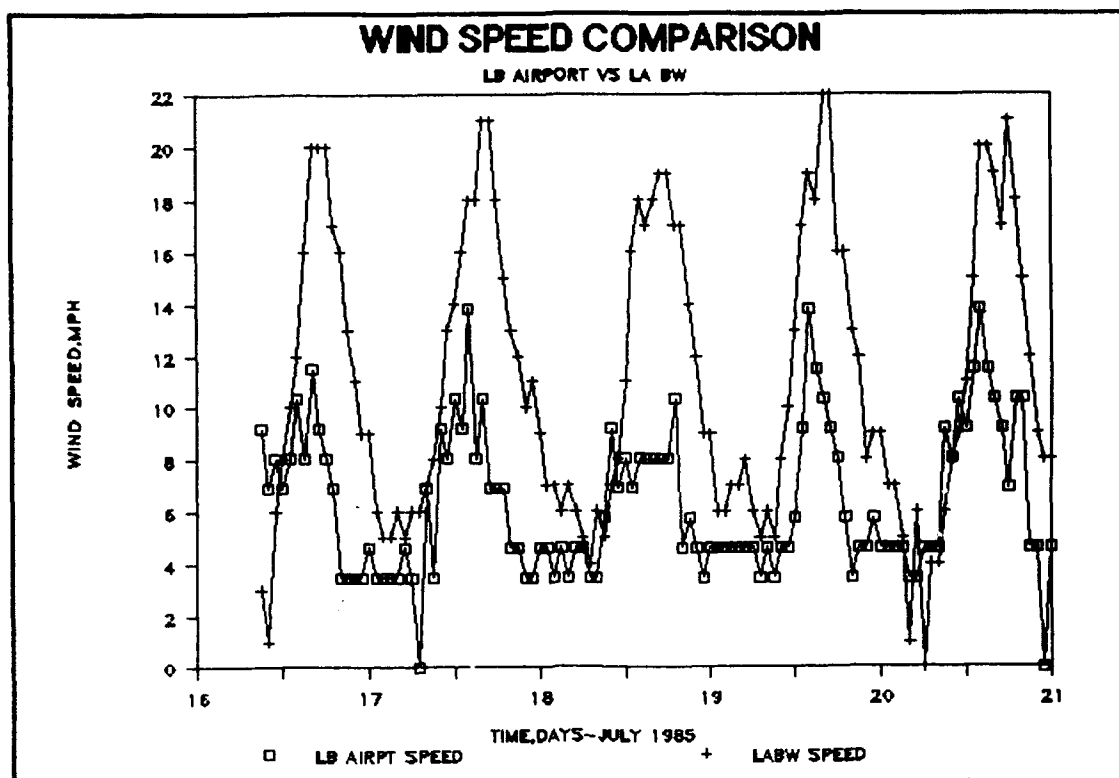


Figure 6. Windspeed and wind direction comparisons between San Pedro Breakwater and Long Beach Airport

Average Wind Speed & Direction at Los Angeles & Long Beach Airports

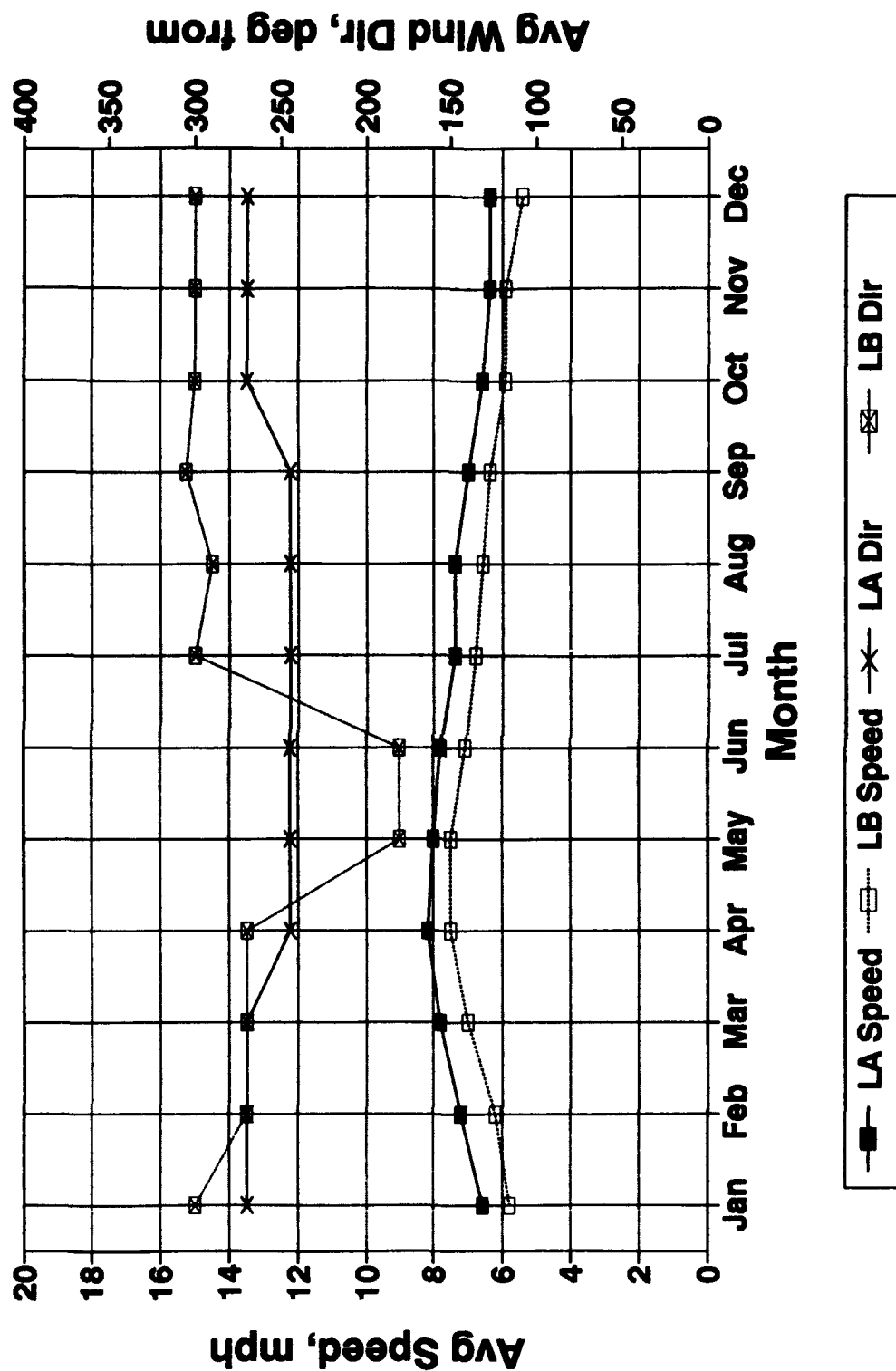


Figure 7. Average wind speed and direction at Los Angeles and Long Beach Airports

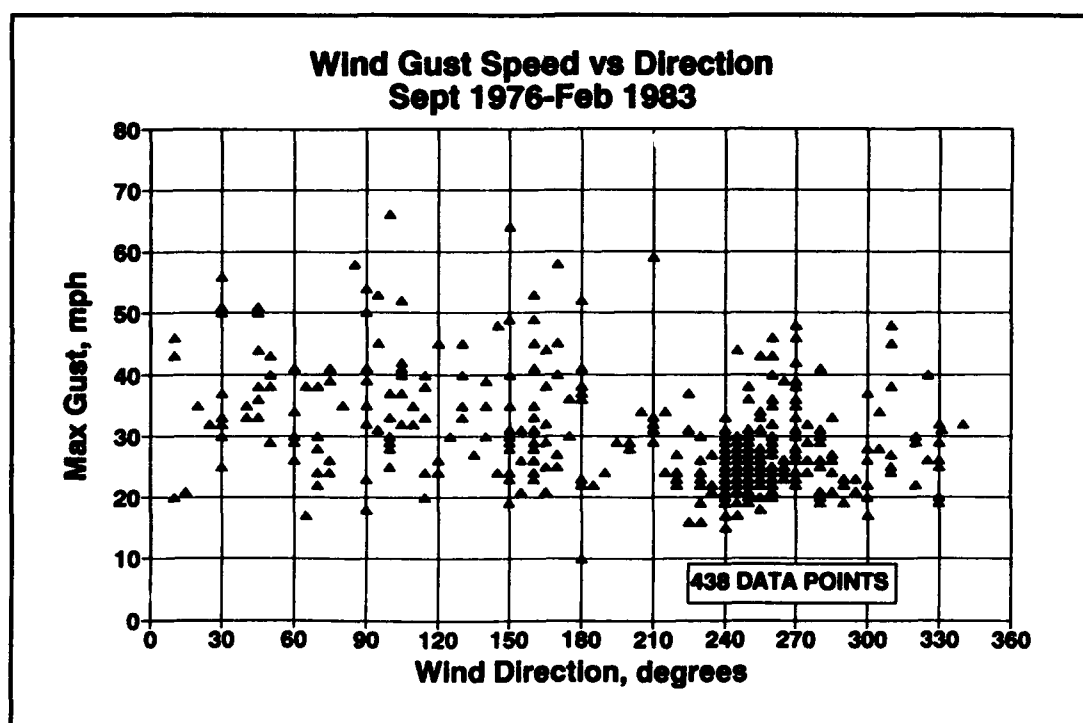
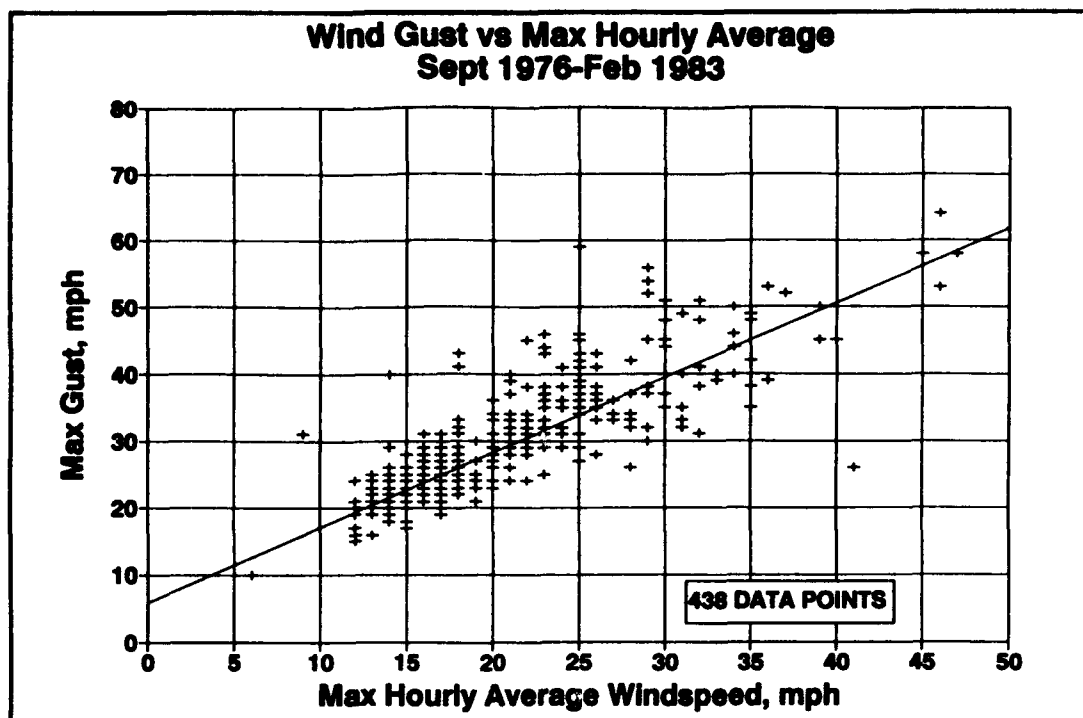


Figure 8. Wind gust speed versus hourly average wind speed and wind direction

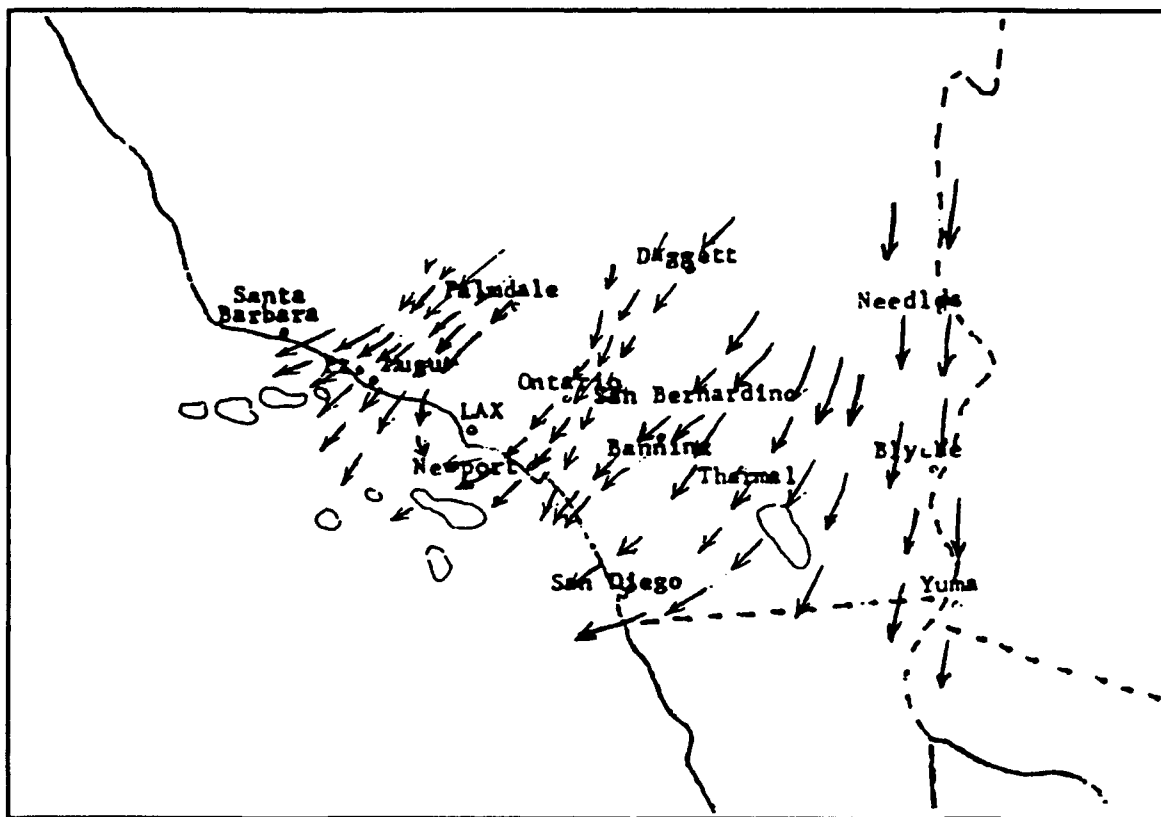


Figure 9. Favored courses of Santa Ana Winds (from Kurtz (1977))

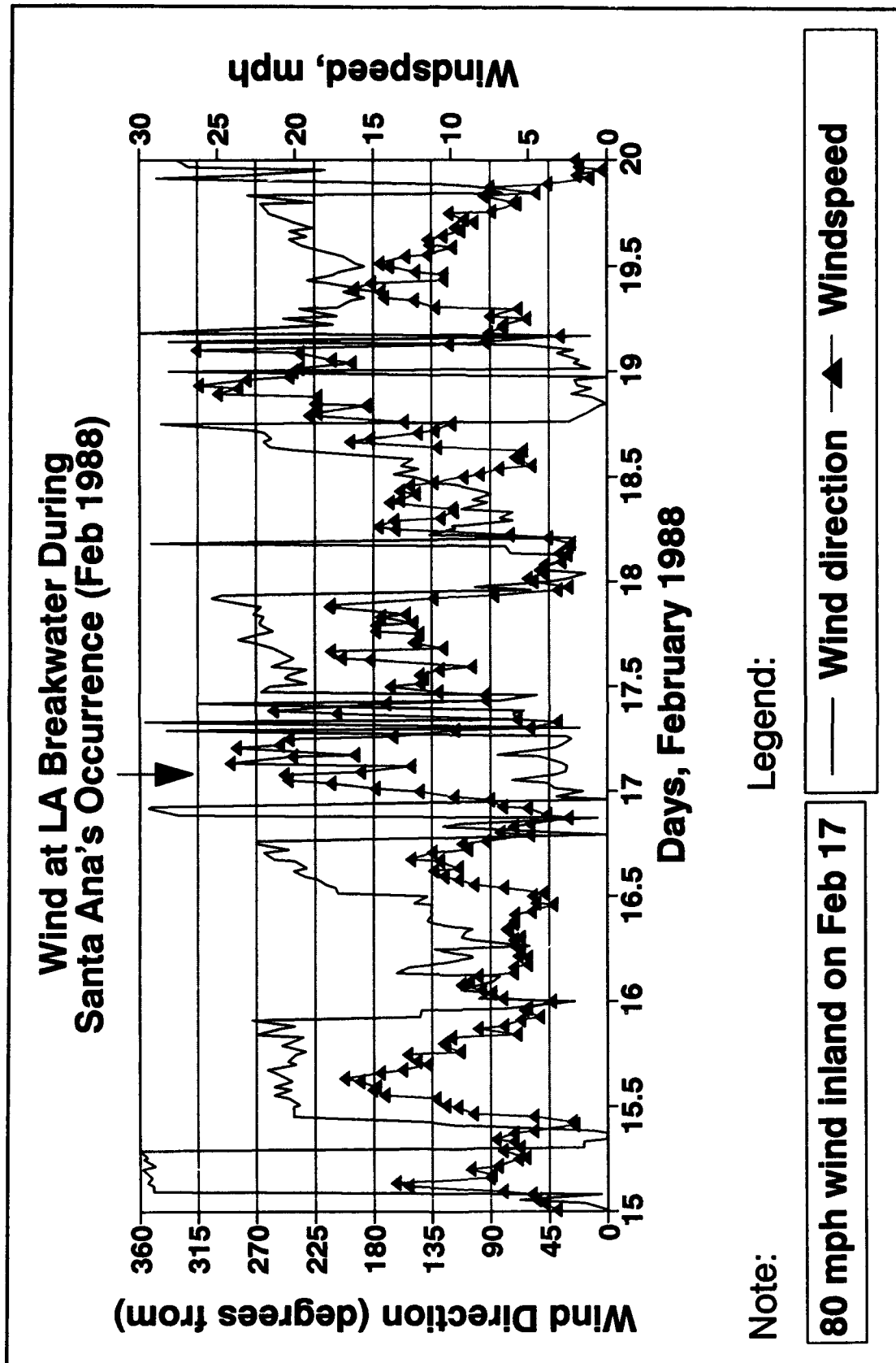


Figure 10. Wind at San Pedro Breakwater during Santa Ana occurrence

3 Selection of Wind and Tide Test Conditions

Based on examination of wind data in Chapter 2, the most significant types of wind conditions with respect to harbor circulation were selected. The previous calibration and verification of the model considered only strong summer diurnal winds.

In this report, four wind conditions are considered. The first is a summer condition characterized by the calibration period in which winds exhibit a typical diurnal cycle with strong afternoon onshore winds. This is called the "existing condition." It was of interest to contrast this condition with a "no-wind" condition to help understand the effect of winds on harbor circulation and provide information about circulation when winds are low, though the diurnal wind cycle is the dominant wind pattern. Next the calibration wind field was shifted in time by 10 hr so the maximum wind speeds coincide with the long ebb flow of higher high water to lower low water rather than the slower flood flow conditions of lower high water to higher high water used in calibration. This is identified as Case 1. Figure 11 shows this wind condition, with time measured from 0000 hr on 1 January 1987 (Pacific standard time). Note 5232 hr corresponds to 0000 hr on 7 August 1987. Direction shown, in degrees from north, i.e., 0 deg is from north, +90 deg is from east, and -90 deg is from west, etc., is the direction from which the wind was blowing. The measured water surface elevation at the offshore boundary used in the calibration is also shown in Figure 11. Following Case 1, two wind conditions (Cases 2 and 3) associated with strong frontal systems were investigated. Case 2 was for winds from the southeast and Case 3 for northwest winds. These selected events are described in detail in Chapter 5. Tidal conditions used for Cases 2 and 3 were the same as for Case 1 (and the model calibration) since no prototype boundary tidal conditions were available for these events. This was probably not significant for Case 2 since wind was from the southeast, from the ocean toward the harbors, as calibration winds were from ocean to harbors. For Case 3, winds were from the northwest, from the harbors to the ocean, so boundary effects may be present due to the significant change in wind-field orientation. However, the focus of the study was on harbor circulation behind the breakwaters, distant from the boundary, which should permit a reasonable

understanding of the effects of northerly winds on harbor circulation until prototype tidal information can be collected during fall-winter events.

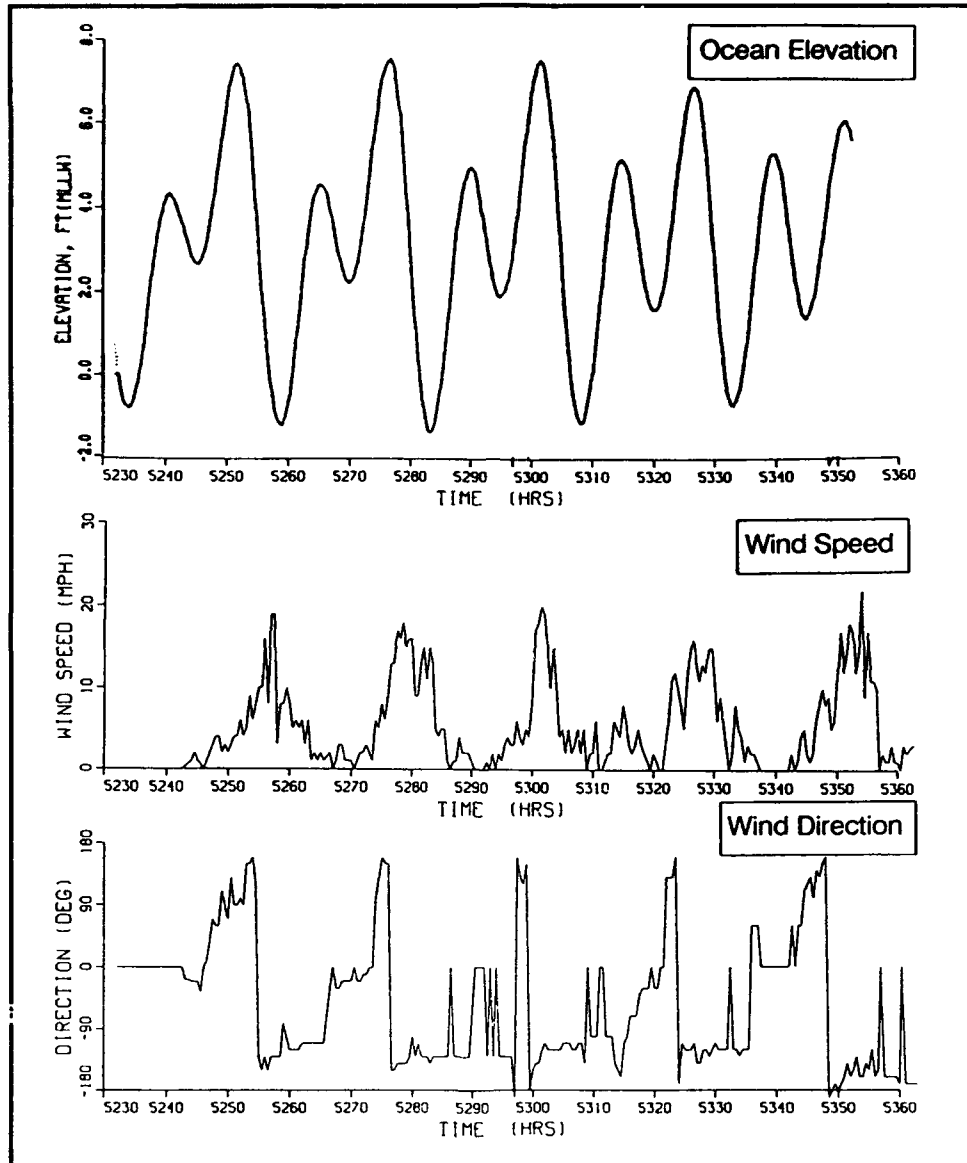


Figure 11. Wind and ocean boundary conditions for Case 1

4 The Computational Model

The hydrodynamic model used was a modified version of the CH3D model developed originally by Sheng (1986), with many changes having been made by WES. The model can simulate time-varying 3D hydrodynamics due to tides, wind, river inflow, and density currents induced by salinity and temperature gradients. In the horizontal plane, computations can be made on Cartesian or boundary-fitted grids. In the vertical, the model employs sigma stretching, which permits the same number of layers in shallow and deep portions of the water body. As depths increase, the vertical extent of each layer increases proportionately. Johnson et al. (1989) give additional details.

Numerical Grid

In the horizontal, a variable, rectilinear grid, which has sufficient resolution and which was successfully used in previous WES studies of the harbors (Seabergh 1985), was used (Figure 12). The grid had a total of 12,032 horizontal cells (128 cells in the east-west direction and 94 cells in the north-south direction) and was aligned to coincide with the Inner Harbor entrance channels. Minimum cell width was 235 ft. The grid extended 4.2 miles seaward of the middle breakwater and covered an area of approximately 146 square miles. In the vertical, after some sensitivity testing, three sigma-stretched layers were used.

Calibration and Verification

After a careful review of the field data collected in 1987 (McGehee et al. 1989), the periods of 7-11 August and 19-23 August were selected for calibration and verification of the model. The earlier period represented a large spring tide condition, while the later period was near a mean tide. Measured surface elevations at an offshore tide gauge were used for the ocean boundary condition and already contained the effects of winds. Wind data (velocity, magnitude, and direction) measured north of the Los Angeles main channel entrance were used for model calibration and verification. On the basis of sensitivity tests, the winds in the model were blocked off for inner harbor channel cells to account for protection due to structures in the surrounding area, which is highly industrialized. Winds over the rest of the study area were assumed to be spatially uniform but varying in time. On the basis of

several sensitivity runs, the following values were finally selected for model coefficients and parameters for calibration: Manning's $n=0.02$, horizontal eddy coefficient $A_H=20,000 \text{ cm}^2/\text{sec}$, and vertical eddy coefficient $A_V=10 \text{ cm}^2/\text{sec}$. A time-step of 60 sec was used for both external and internal modes. The wind drag coefficient was selected according to Garrat (1977). Additional details are given in CERC (1990).

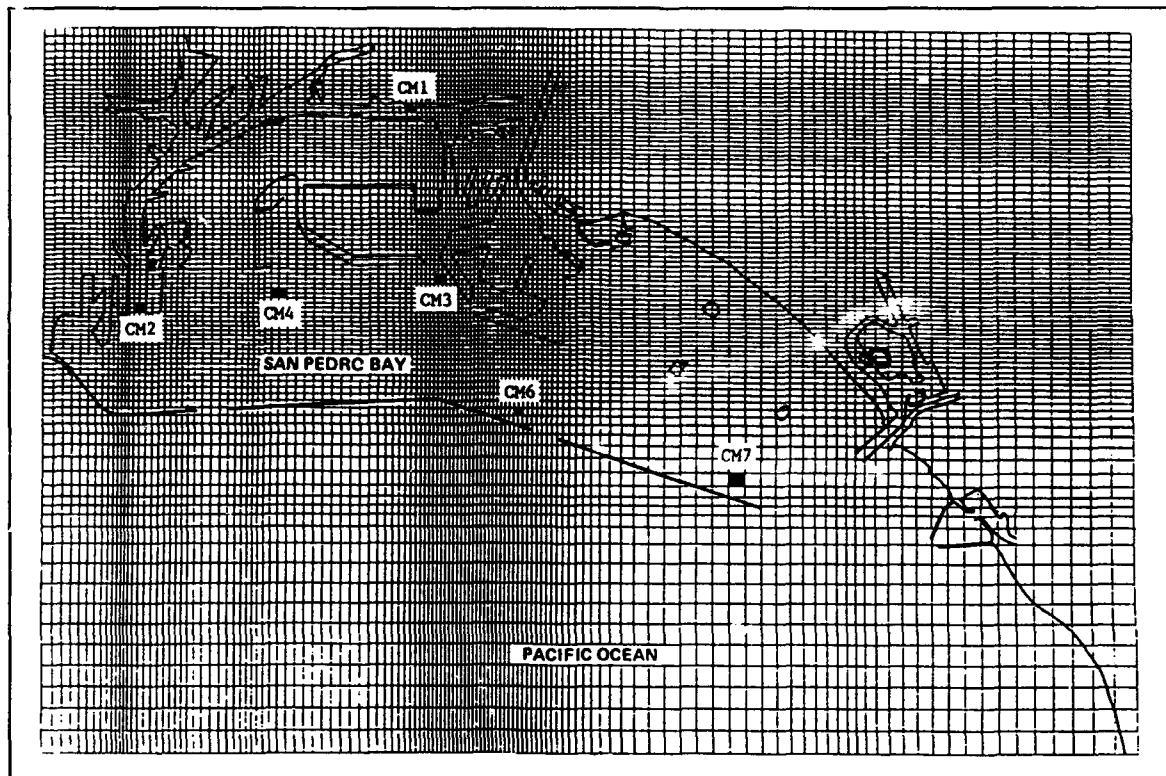


Figure 12. Model grid and location of prototype current meters

5 Model Simulations

Circulation for No Wind and Case 1

To determine circulation patterns, velocity vectors were plotted at each vertical layer (surface, mid-depth, and bottom) at every third cell. Figure 13 shows model results at hr 5283 (lower-low water condition following the long ebb runout). In Figure 13, the top plots are for a no-wind condition and the bottom plots are for Case 1, with wind actively blowing over the harbors at hr 5283. The plots for no wind show a gyre in the outer harbor, set up by countering flows through Angel's Gate and the West Basin (Ranges 1 and 3 respectively, Figure 14). The gyre becomes stronger from the bottom to the surface. This circulation was typical of previous two-dimensional (2D) studies. An apparent net eastward (left to right in Figure 13) movement is seen in the region behind the middle breakwater. Note the relatively low velocities. Even during times of maximum ebb and flood flow, currents in the harbors are generally less than 1 fps. Only currents through the entrances exceed that level during strength of tide. The "active wind field" (Case 1) snapshots indicate a strong easterly surface flow with increasing counterflow (westward) in the mid-depth and bottom layers. In the western and central regions of the harbor adjacent to the breakwaters, bottom currents toward the west are predominant.

The net bidirectional flow pattern (Case 1, surface flow toward the east and bottom currents toward the west) demonstrated by the 3D model is seen in prototype data also. Two summer months of data collected in 1987 at two moored current meters (CM6 and CM7, locations shown in Figure 12) support the model result (Figure 15). Current meter CM6S just inside Queen's Gate shows strong net easterly flow on the surface. The bottom currents (CM6B) exhibit more diversity in direction due to their proximity to the harbor entrance at Queen's Gate. Gauge CM7S shows net easterly surface current and CM7B shows net westerly bottom current on the eastern side of the harbors.

An interesting comparison can be made between results for net circulation obtained with the present 3D simulation with wind (existing condition) and the 2D, no-wind, tide-only simulations used in previous WES studies of the harbors (Table 2). For the 2D case, net flow is from the ocean into the harbors through Angel's and Queen's Gates and out through the east

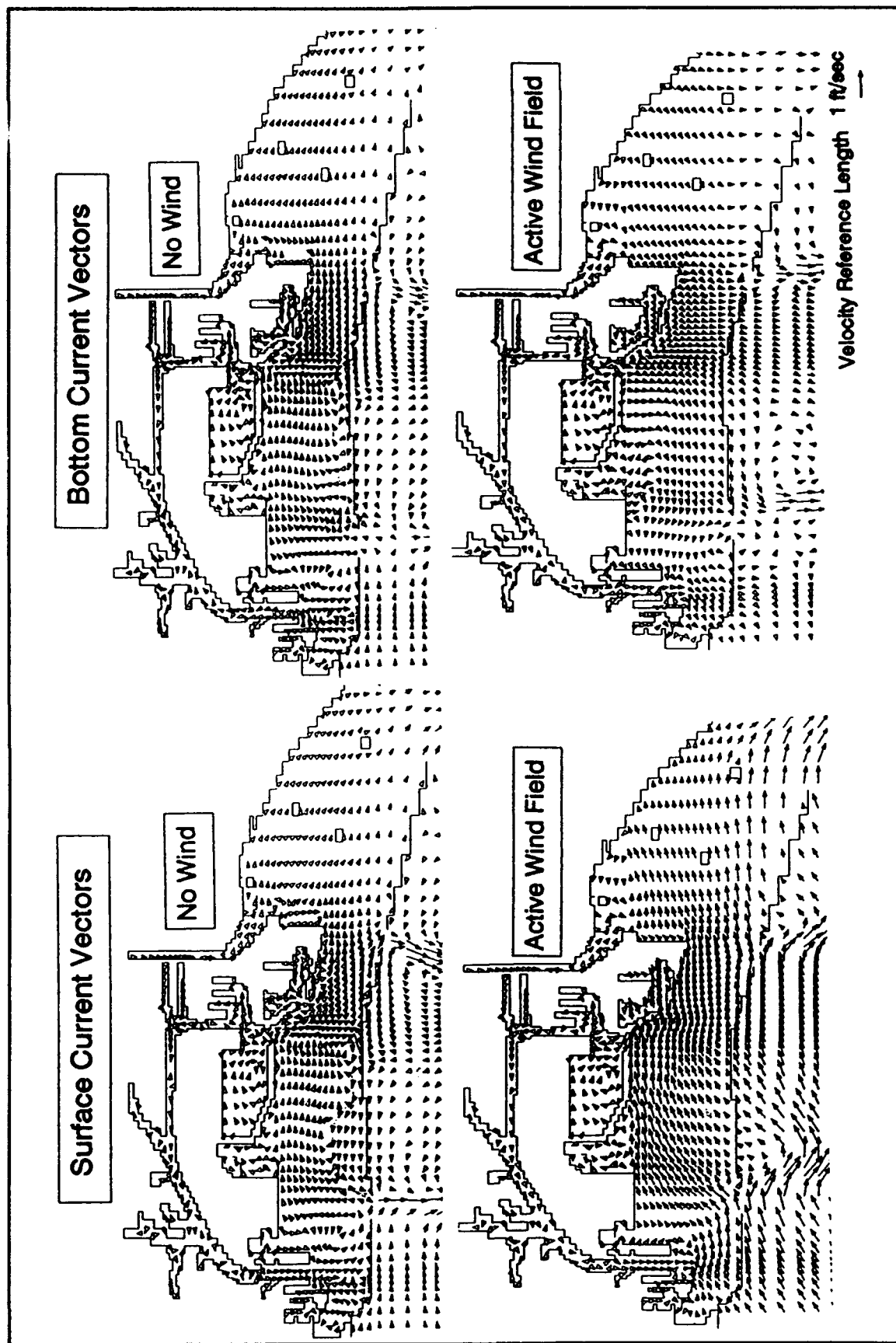


Figure 13. Current vectors at hr 5283

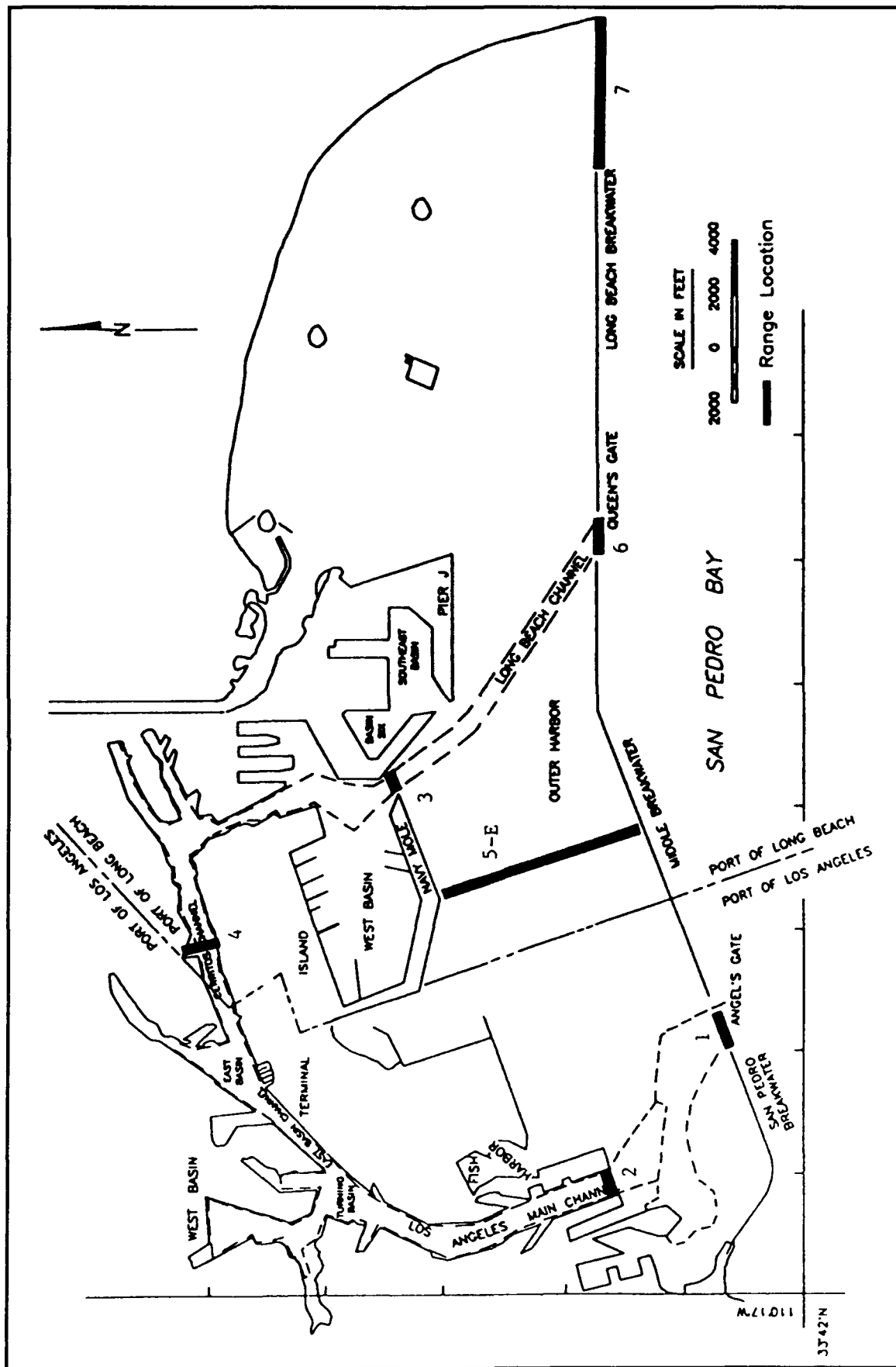


Figure 14. Flow discharge range locations

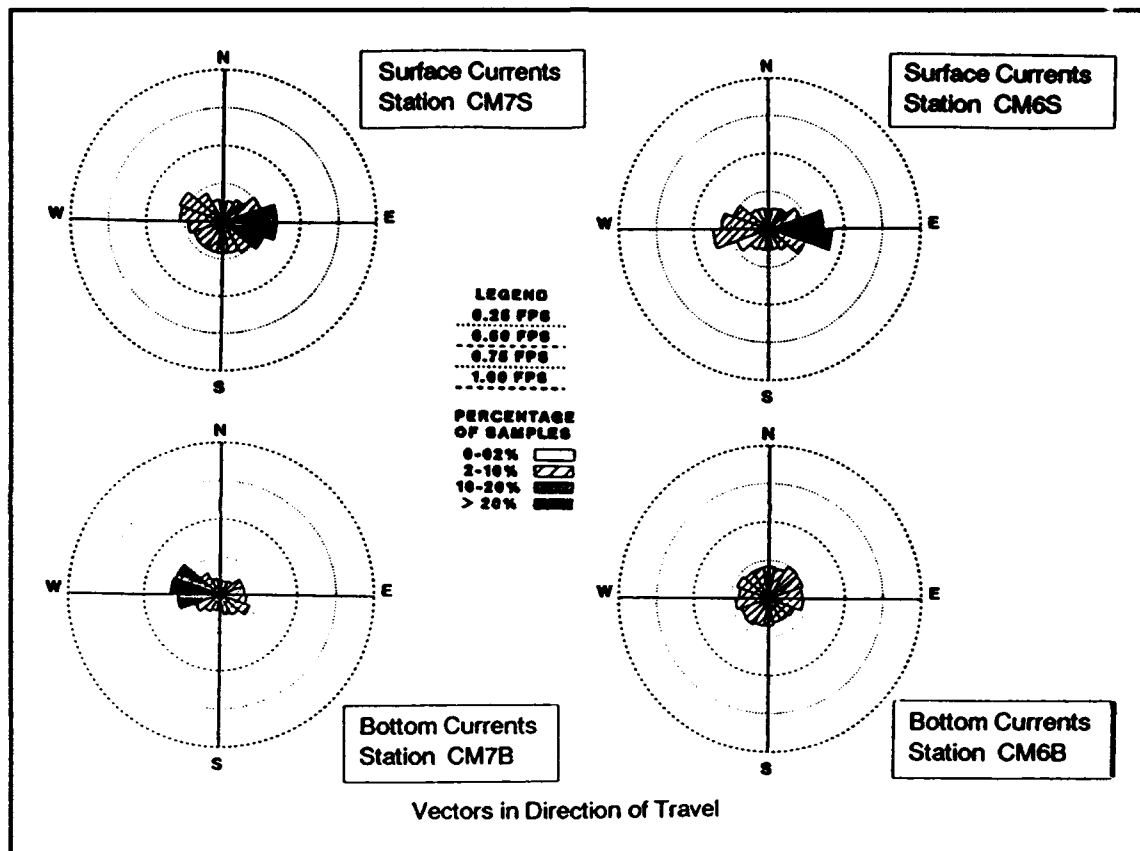


Figure 15. Prototype current vector roses at stations CM7 and CM6

breakwater gap. For the 3D case, net flow is smaller and from the ocean into the harbors through Angel's Gate and out through Queen's Gate and the east breakwater gap. Thus 2D model results, in terms of flow volumes at the three harbor entrances, indicate a stronger net circulation to the east than given by the 3D model. This is contrary to the normal expectation that the inclusion of net eastward-directed winds in the 3D model would promote a stronger net circulation to the east. This behavior may be explained by the fact that the relatively deep nature of the harbors permits the return flow of water to Angel's Gate and Queen's Gate, rather than major net movement toward the east breakwater gap, as would be true for a shallow harbor.

Table 2
Distribution of Net Flow Into (+) or Out of (-) Harbor as a Percent of Total Flow Volume Into Harbor

Location (Range)	3D Model	2D Model
Angel's Gate (1)	4	7
Queen's Gate (6)	-3	9
East Gap (7)	-1	-16

Case 1 versus Existing Condition

The Case 1 shift of 10 hr in the timing of wind (so that maximum winds occurred during strongest ebb flow) produced changes in discharges in the outer harbor (Range 5, Figure 16 and Plate 31) and at harbor gates (Ranges 1, 6, and 7, Plates 27, 32, and 33, respectively). Other discharge ranges in the inner harbor showed no change (Plates 28-30). Positive discharge is eastward at Ranges 4 and 5, and northward at the other ranges. Downward arrows in Figure 16 indicate when maximum wind was blowing for each condition. It is clear that at Range 5, whenever the wind velocity for a particular condition was at its peak, the discharge was greater than the discharge for the other condition. Comparing the two curves, one can estimate that the net effect over several days is close to zero; i.e. the occurrence of westerly winds relative to the phase of tidal currents has no significant effect except in the short term. When strong westerly winds occur during flood flows, discharges are increased slightly through Angel's Gate and decreased at the east breakwater gap, enhancing eastward flow. When strong westerly winds occur during ebb flow, ebb discharge is decreased at Angel's Gate and increased at the east breakwater gap, once again enhancing net eastward flow.

Figure 17 shows locations where current magnitude and direction measurements were sampled for the three layers. Layers 1, 2, and 3 correspond to bottom, mid-depth, and surface currents, respectively. Examination of Plates 34-54 shows only small changes in velocities and direction. Plates 55-58 indicate no change in tidal elevations. The existing condition data plots directly on top of the Case 1 data. Plates 59-70 show the current vector snapshots for various tidal conditions

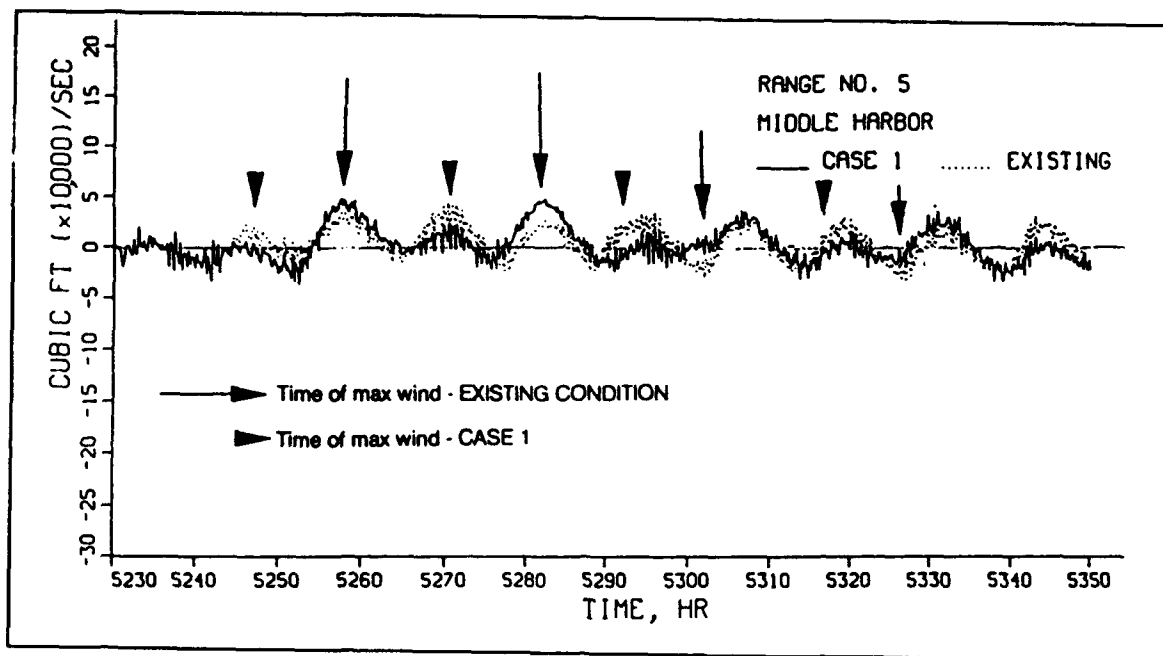


Figure 16. Discharge through Range 5 for Case 1

for the three layers (or levels). Plates 59-61 at hr 5283 show currents at low water, plates 62-64 show mid-tide flood currents at hour 5298, plates 65-67 show slack highwater currents at hr 5301, and plates 68-70 show ebb currents at hr 5304. These current snapshots can be compared with results for Cases 2 and 3, as the patterns are very similar to those of the existing condition tests.

Case 2: Winds from the Southeast

The wind speed and direction for this case are based on a prototype event of 15-18 December 1987. Figure 18 shows the large pressure drop associated with this system. Figure 19 shows wind speed and direction derived from smoothing the actual data. The winds start at 5242 hr and build up over 18 hr from zero speed to a maximum of 31 mph, which remains constant for 6 hr from a direction of 115 deg. During the next 36 hr, wind speed drops to 12.5 mph and direction changes to 0 deg (from the north). Thereafter, the northerly winds continue at 10 mph. The timing of peak winds was selected to be in phase with the flood tide.

For this case, discharges across major ranges were compared with those for existing conditions; that is, results for the model calibration with summer winds (Plates 71-77, see Figure 14 for locations). Comparisons show that the effects of winds predominate over those of tides. Over a 40- to 60-hr period from 5240 to 5300 hr, there is only net inflow up to 350,000 cfs through the east breakwater gap (Plate 77) and net outflow through Angel's (Plate 71) and Queen's Gates (Plate 76) with maximum flows of 280,000 and 165,000 cfs, respectively. In the outer harbor, flow is directed west during this period

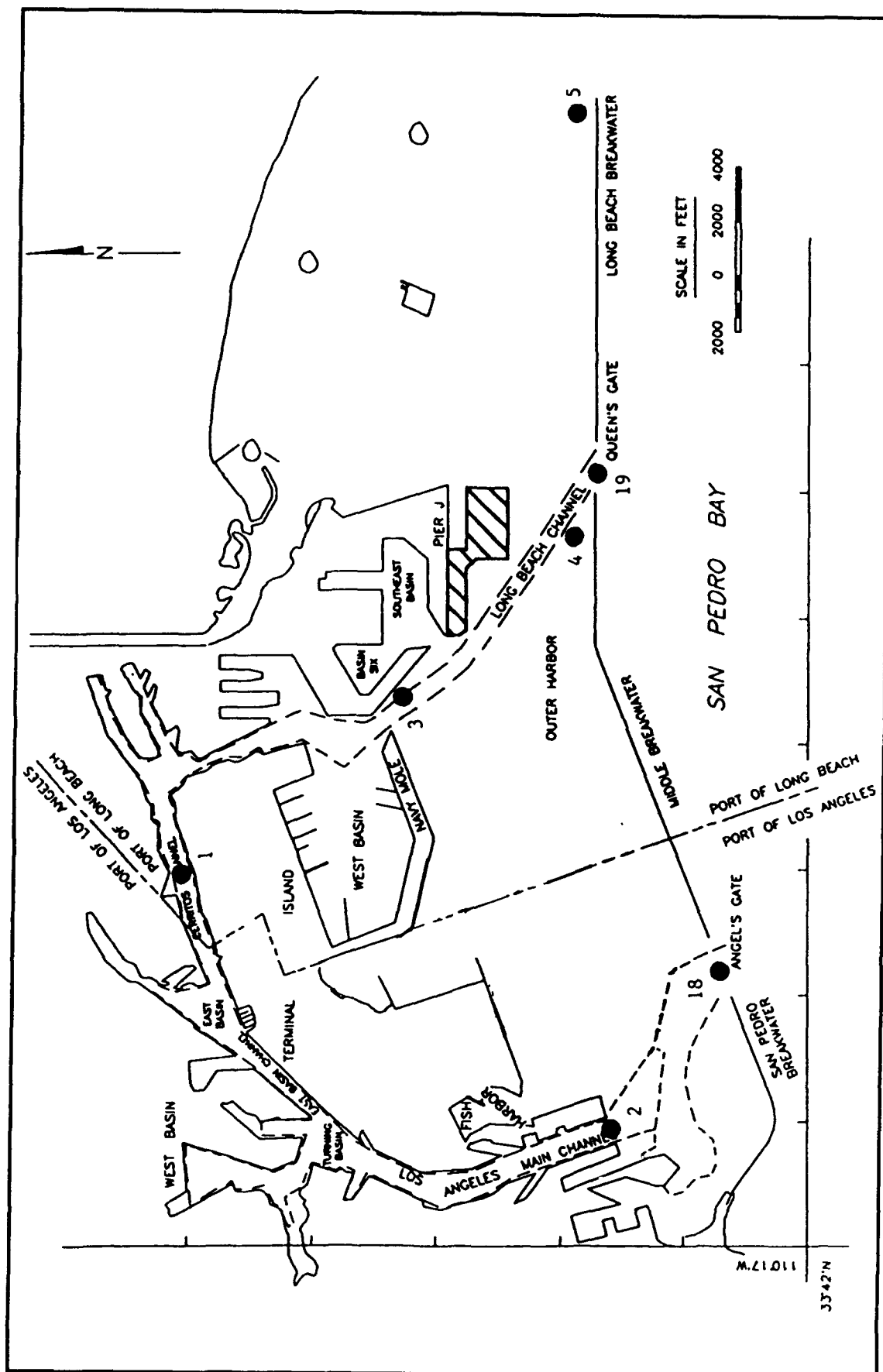


Figure 17. Model tide and current gauge locations

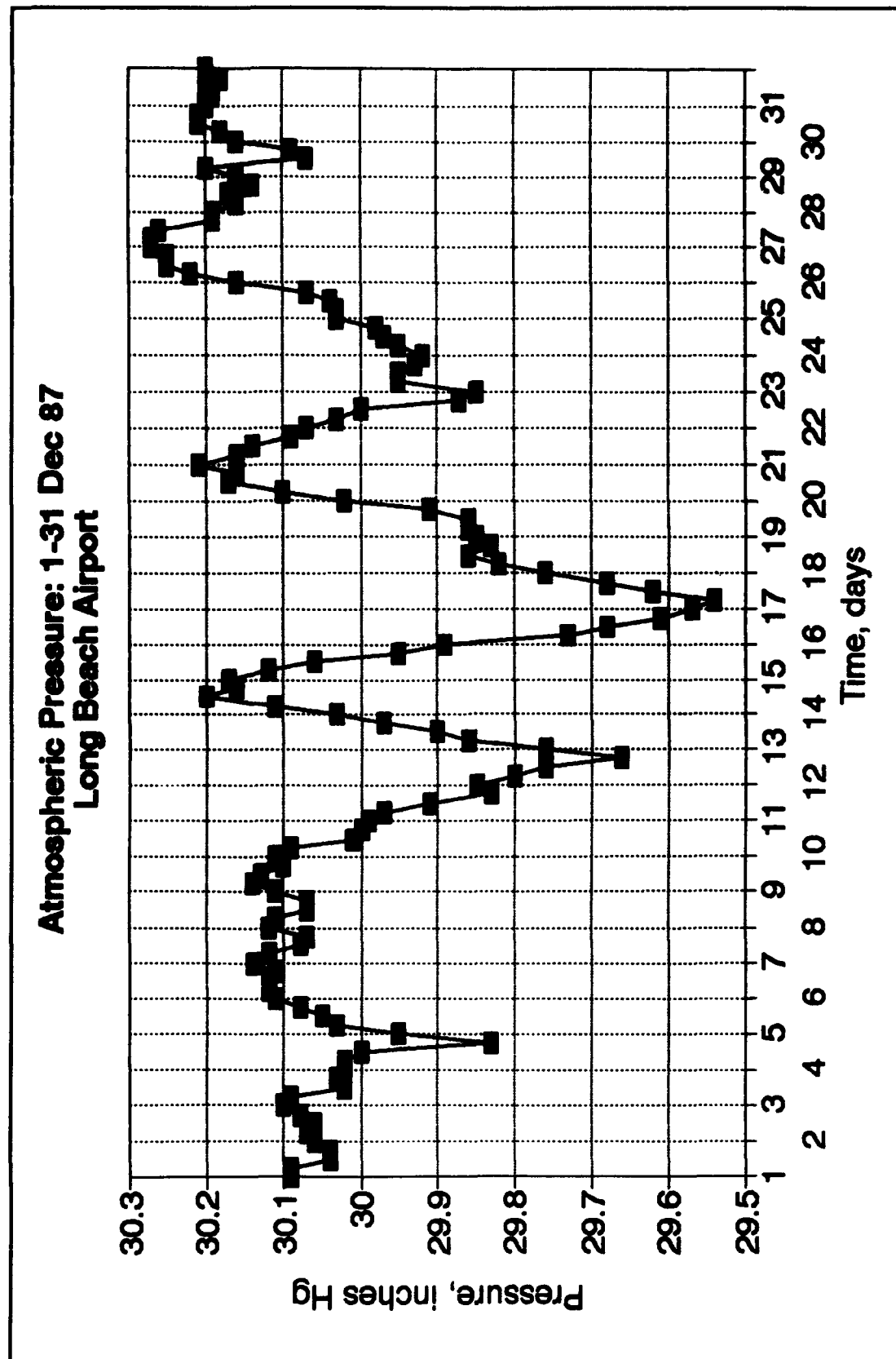


Figure 18. Atmospheric pressure variations during 1-31 December 1987

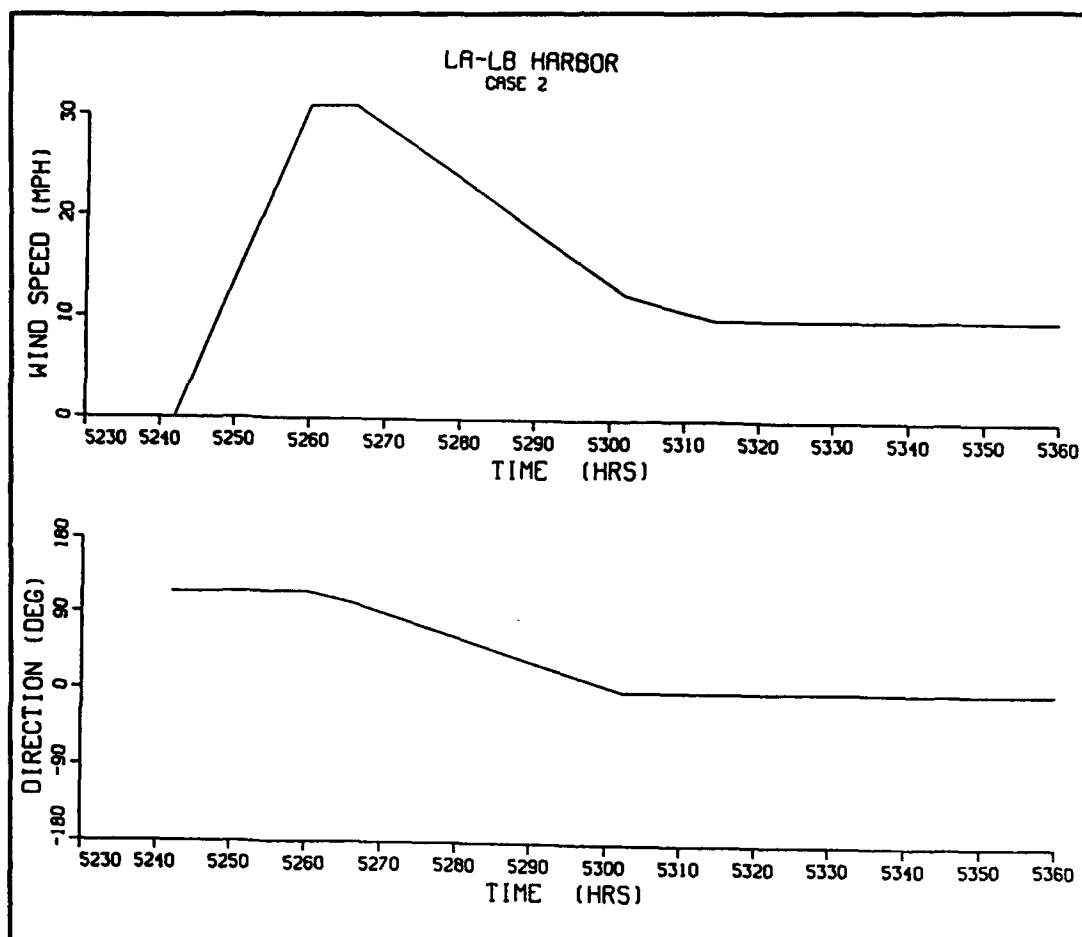


Figure 19. Wind conditions for Case 2

with a maximum discharge of 220,000 cfs through Range 5 (Figure 20), and net flow volume during this event, through Range 5, about equal to that of the total harbor volume. Circulation in inner harbor channels is clockwise from Los Angeles to Long Beach, in contrast to counterclockwise circulation for existing conditions.

Time series of velocity (Plates 78-98) indicate that at the harbor entrances, velocities at the surface layer are large (3.5 to 4 fps; Plates 92, 95, and 98). At the East breakwater (Gauge 5), currents in the bottom layer (Plate 90) are out of the harbors and currents in the mid-depth and surface layers (Plates 91, 92 and Figure 21) are into the harbors. At Angel's and Queen's Gates (Gauges 18 and 19), currents in the bottom and mid-depth layers (Plates 93-94 and 96-97) are out of the harbors. In the surface layer (Plates 95 and 98), currents may be either into or out of the harbors, depending on the phase of the tide. The tidal signature can be seen clearly in the plots for velocities and discharges. Generally, there is a transition in velocity magnitude and direction from top to bottom. Large changes in velocity magnitude, from 0.8 fps (existing) to 2.5 fps (Case 2), also are observed in the Long Beach Channel and near the entrance to Long Beach's west basin (Gauges 4 and 3, respectively; see Figure 17 for locations). They may be attributed partly to the fact that the southeast winds are approximately aligned with the channel. A weak circulation gyre is noticeable at all three levels in the Long Beach West Basin.

Tidal elevations (Plates 99-103) indicate only slight variations, primarily during maximum wind velocities (hr 5260-5266). Snapshots of velocity vectors (Plates 104-118) taken at hr 5257, 5263, 5272, 5296, and 5308 show the effect of the rising winds followed by falling winds. It is clear that a return to near normal circulation does not occur until hr 5308, about two days after peak winds.

Case 3: Winds from the Northwest

Wind speed and direction for Case 3 are based on a 22-26 December 1987 event (Figure 22) where the actual data have been smoothed. This event followed that examined in Case 2. Winds started at 5260 hr and built up over 18 hr to 31 mph (direction 0 deg). Speed remained constant for 6 hr and later dropped to 5 mph over 72 hr. Direction stayed the same throughout. Timing of the peak winds was chosen to be in phase with the ebb tide.

In this case also, wind dominated the tide but, overall, this event does not have as much impact on harbor circulation as Case 2. As for the other cases, the results for this case are complicated by several factors, including the temporal variation of wind speed, direction, and phase of tide, the presence of three separate entrances, and vertical variation. Because discharges reflect the vertically integrated effects of the forcing, their variation is shown in Plates 119-125. In general, there are two different circulation regimes, with the transition occurring between 5280 and 5290 hr. In the early regime, there is net inflow through Angel's and Queen's Gates (Plates 119 and 124) and

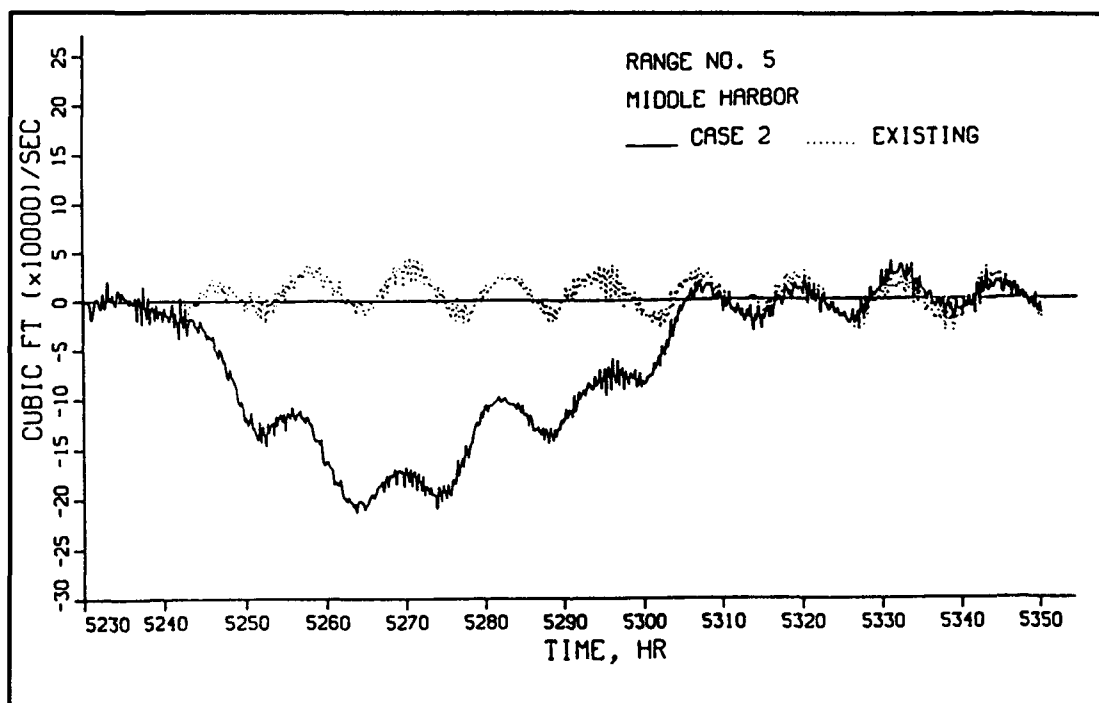


Figure 20. Discharge through Range 5 for Case 2

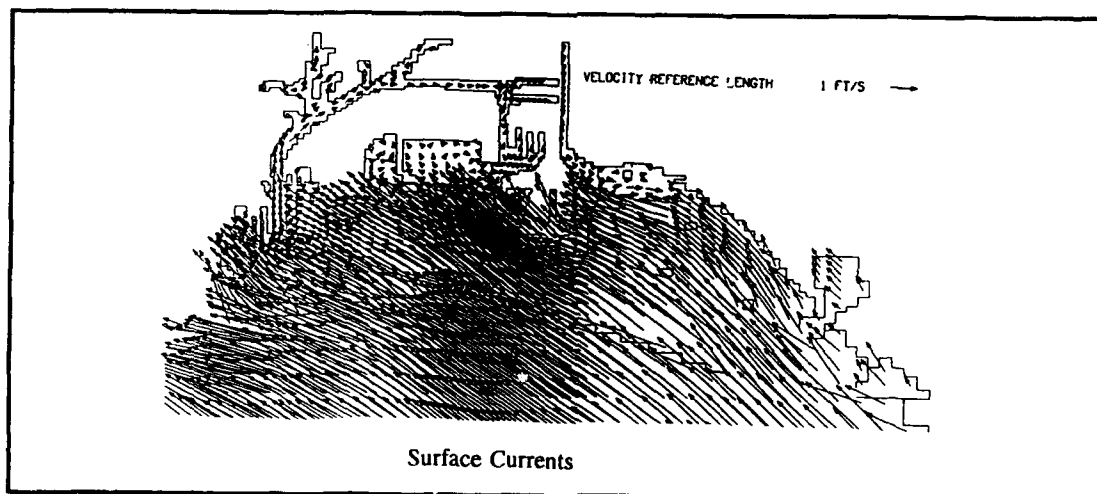
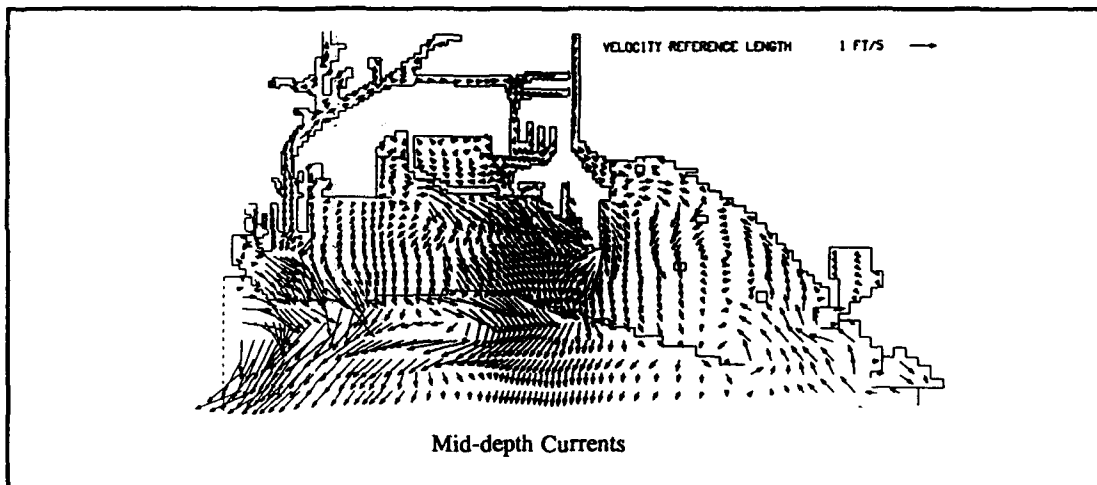
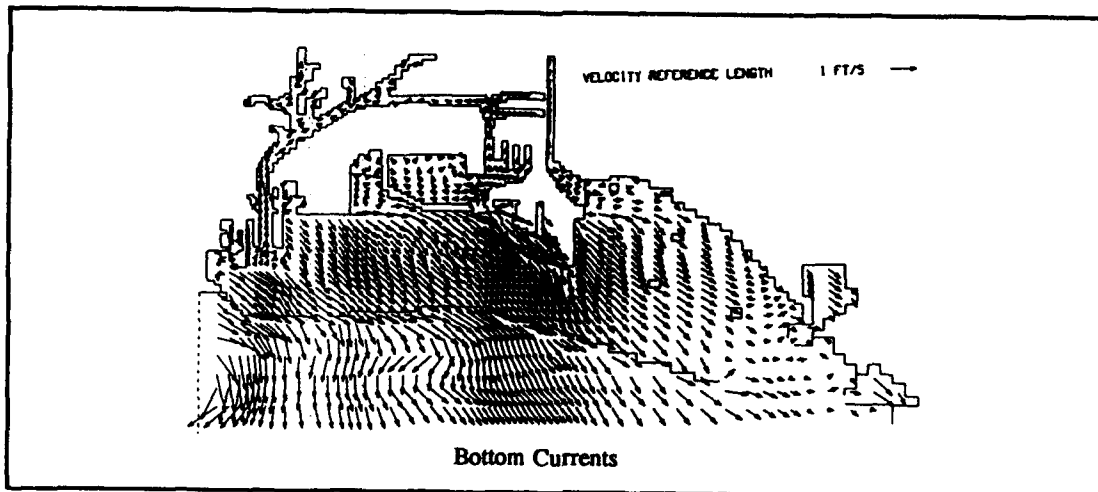


Figure 21. Current vector snapshots for Case 2 at hr 5260

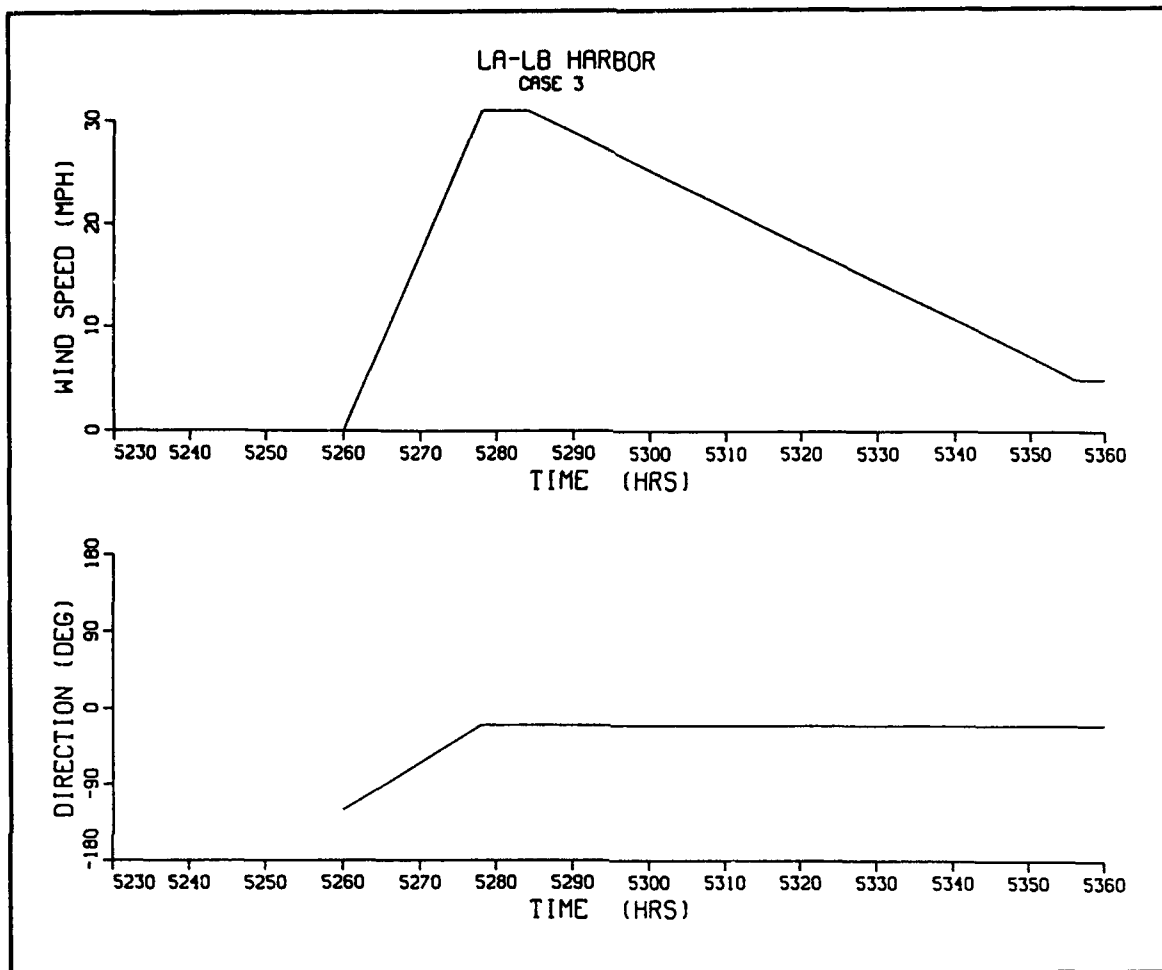


Figure 22. Wind conditions for Case 3

outflow through the east breakwater gap (Plate 125). Consequently, the flow at the Middle Harbor (Plate 123) is directed east. In the later regime, there is outflow through Angel's and Queen's Gates and inflow through the east breakwater gap, with the result that flow at the Middle Harbor is directed west. During peak winds, net flow through the Middle Harbor is four times the normal eastward flow and maximum ebb discharge at the east breakwater gap is doubled to 300,000 cfs. The longer term effect on discharges for Case 3, when compared to Case 2 (for example, Plate 125 compared to Plate 77), results because of the slower decline in wind speed and the steady wind direction for Case 3.

Time series of velocity (Plates 126-140; plots for Gages 18 and 19 are not included) show that at all three entrances, velocity magnitude increases at all three layers. Strong surface currents (order of 3 to 4 ft/sec) are directed in. Dramatic velocity change is observed at the entrance to the West Basin (Gauge 3, Plates 132-134) also. Tidal elevation plots (Plates 141-145) show no significant change in surface elevation. Snapshots of velocity vectors (Plates 146-157) are included. Figure 24 shows the current pattern at all three levels at 5278 hr. In general, the snapshots show that during peak winds, surface currents in the Outer Harbor are southward whereas bottom and mid-depth currents are northward. In general, some minor effects due to reflections from the offshore boundary may be present in model results for the later part of the simulation. They do not change the main conclusions reported here.

Effect of Wind on Circulation in Ship Basins

As shown above, wind events can have significant effects on circulation in harbors. However, it is important to note that everyday wind conditions can contribute to improved circulation in closed-end ship basins. Figure 25 compares a no-wind condition with the calibration condition, which includes typical winds from the west-southwesterly direction. The example shown is for Scheme B, Phase 1 of the Operations, Facilities, and Infrastructure 2020 Requirements Study. Surface currents are aligned with the wind. Examining some of the closed slips, especially the one adjacent to Pier 300, surface currents are into the basin, while mid-depth and bottom currents are exiting the basin, indicating a turning over of the water mass. In contrast, for the no-wind situation, currents are slower and unidirectional.

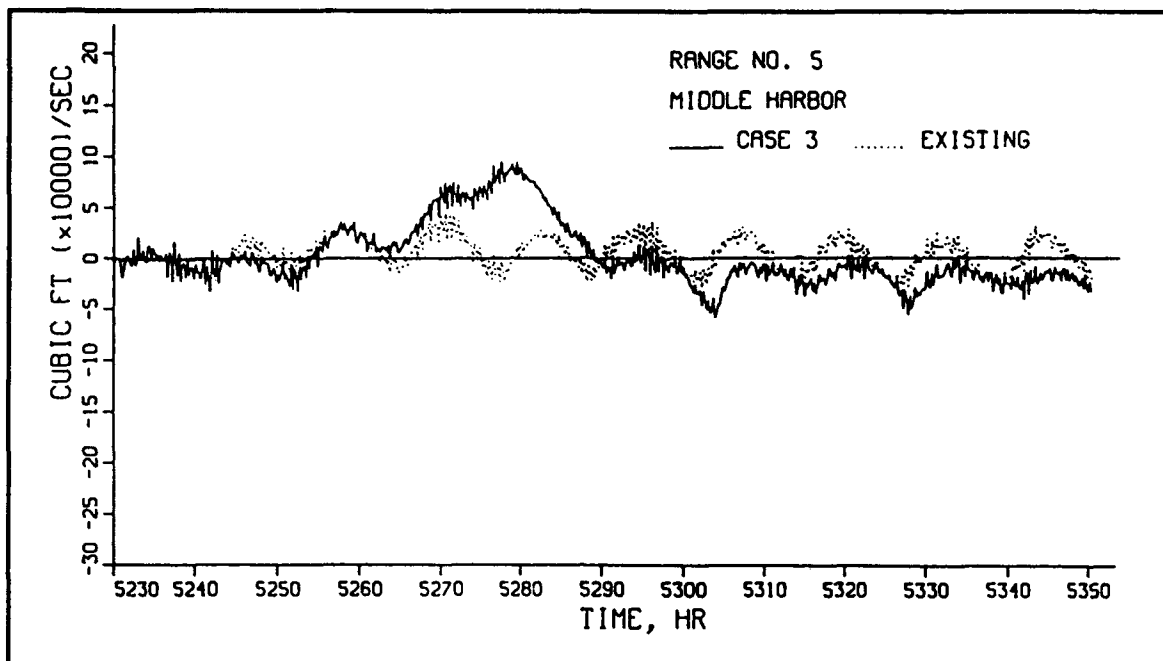


Figure 23. Wind conditions for Case 3

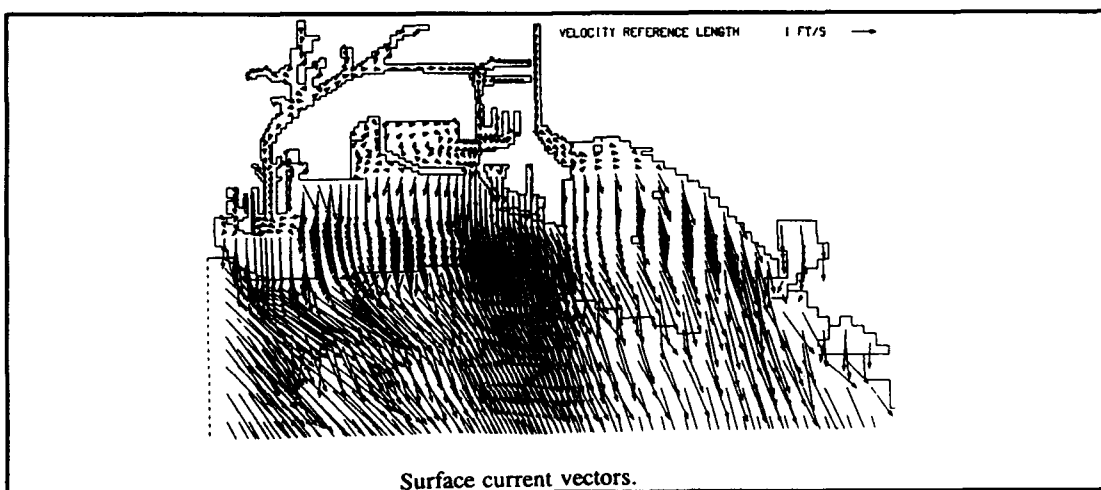
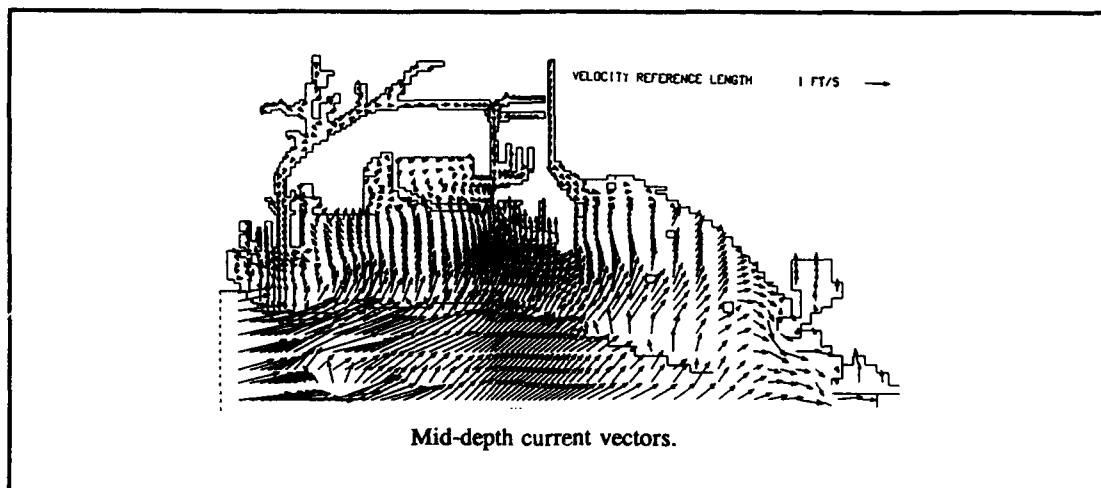
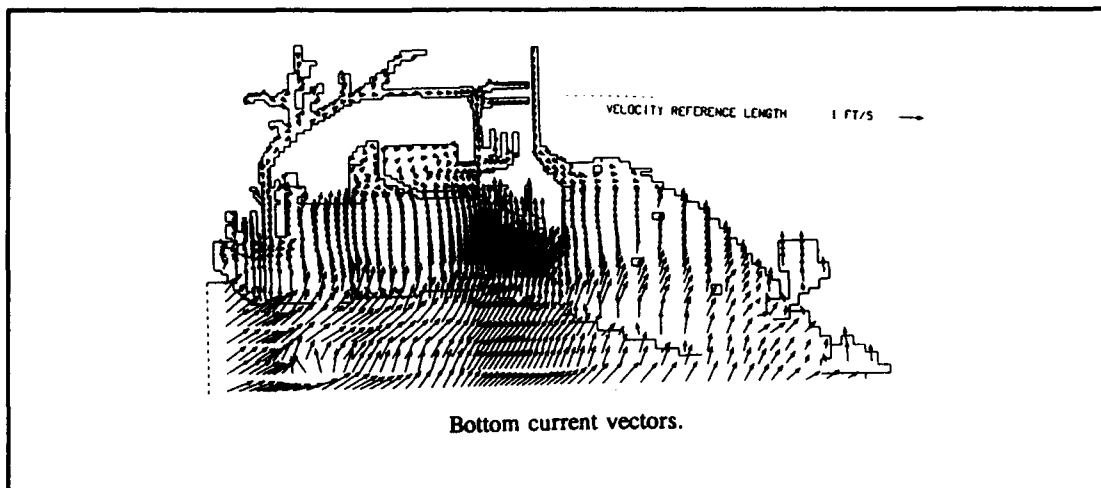


Figure 24. Current vector snapshots for Case 3 at hr 5278

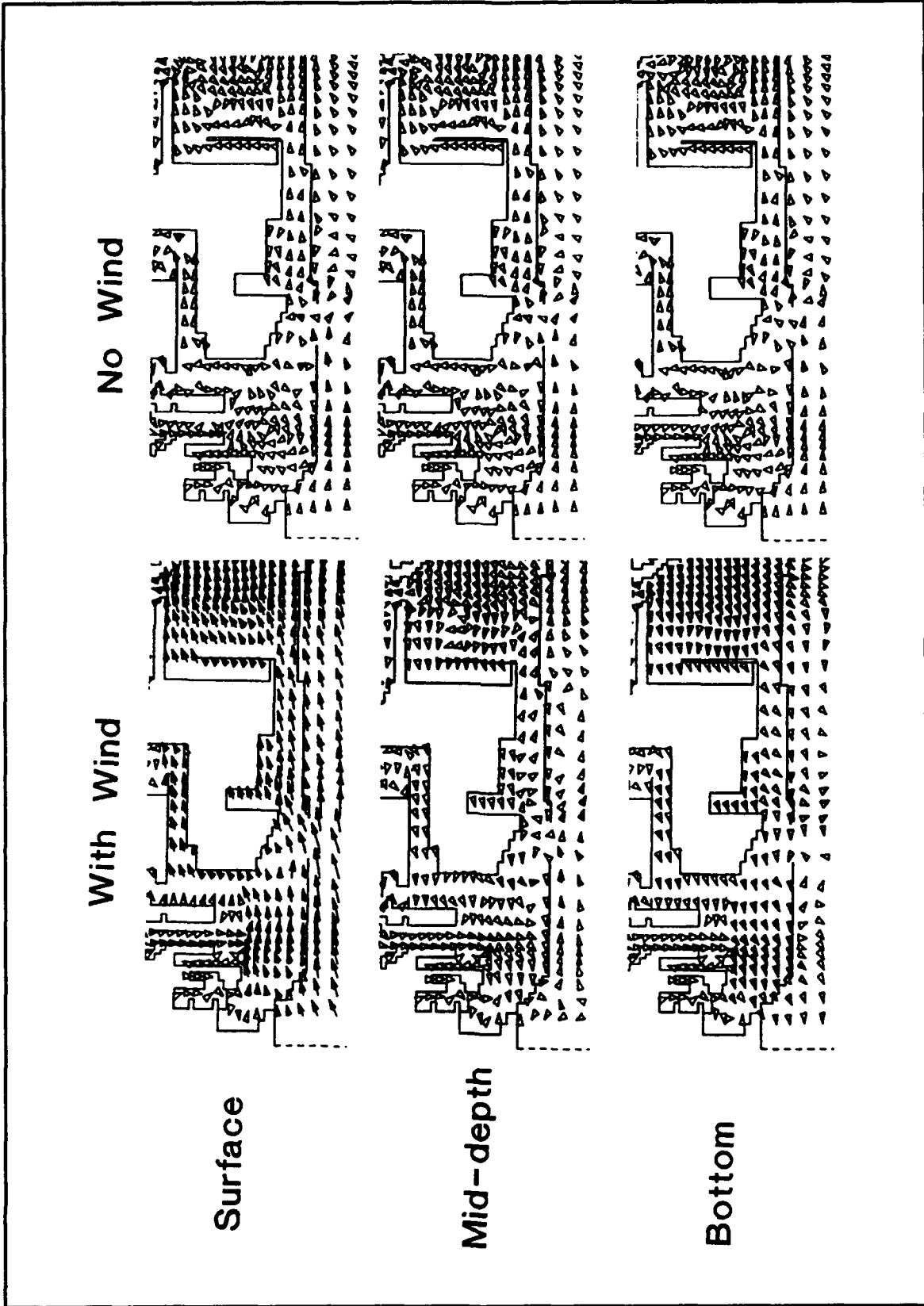


Figure 25. Effect of wind on ship basin circulation

6 Summary and Conclusions

Simulations of harbor circulation with a 3-D hydrodynamic model indicate the following:

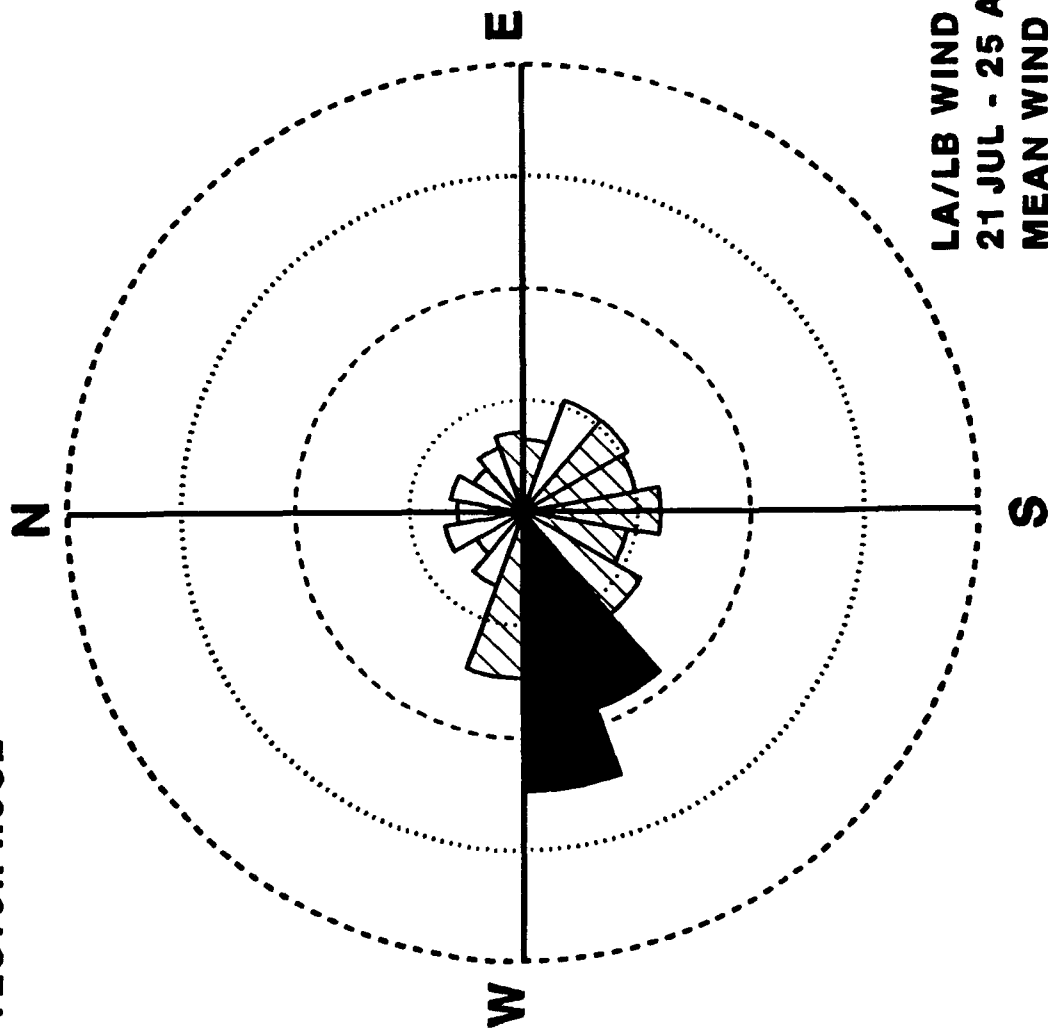
- a. For no-wind conditions, there is a gyre in the LA/LB outer harbor, which becomes stronger from bottom to top, and a net eastward flow through the harbors.
- b. For typical summer winds from the southwest, the surface gyre in the outer harbor is eliminated when winds are actively blowing and reduced when winds are not; the gyre is present at mid-depth and increases in strength at the bottom when winds are actively blowing; net eastward flow through the harbors is not increased by typical winds from the southwest; phasing of winds with respect to tides (Case 1) does not significantly alter circulation patterns over the longer term (order of days).
- c. For Case 2, corresponding to strong winds (31 mph) from the southeast, associated with an approaching front, the effects of winds predominate over those of tides; over a 40- to 60-hr period, there is only inflow through the east breakwater gap and outflow through Angel's and Queen's Gates, a dramatic change from existing conditions.
- d. For Case 3, corresponding to strong winds (31 mph) from the northwest, winds dominate the tide, with velocities at the surface generally directed out of the harbors, and velocities at bottom and mid-depth directed in. Major changes are observed in net flow at Range 5 through the center of the outer harbor and the east breakwater gap as well as velocities at the entrances, compared with existing conditions.
- e. In summary, effects of winds on harbor circulation can be significant, with circulation during storms (such as Cases 2 and 3) being dramatically different from that for normal summer winds. This should be duly taken into account in harbor design and operation.

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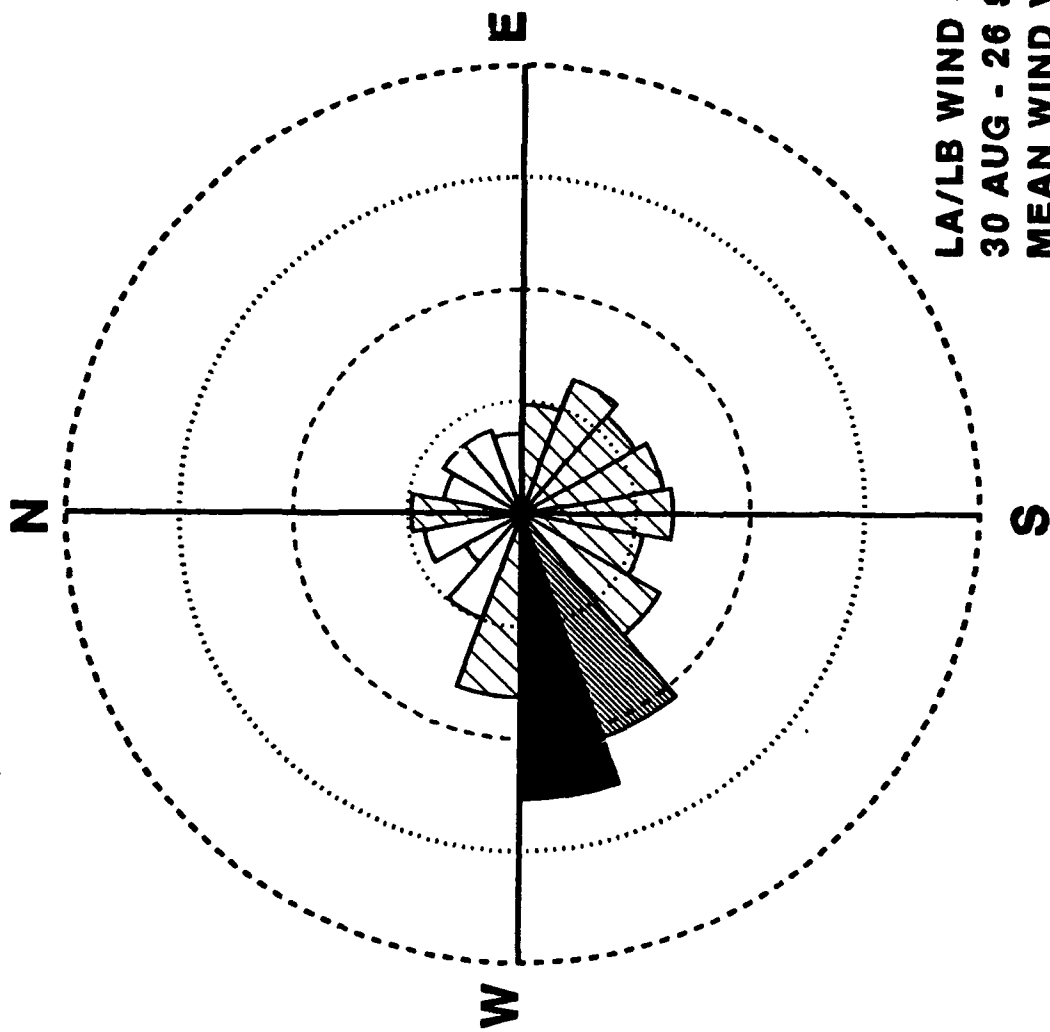
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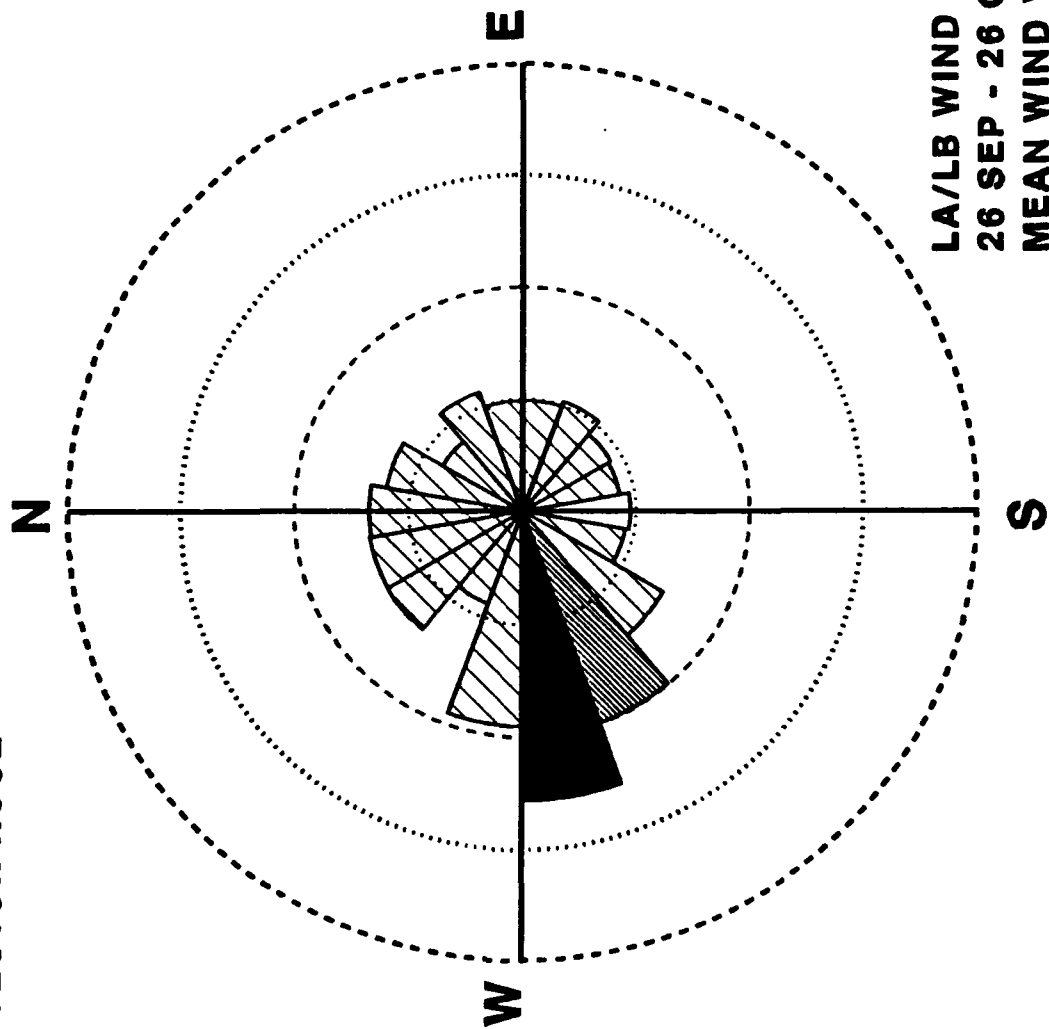


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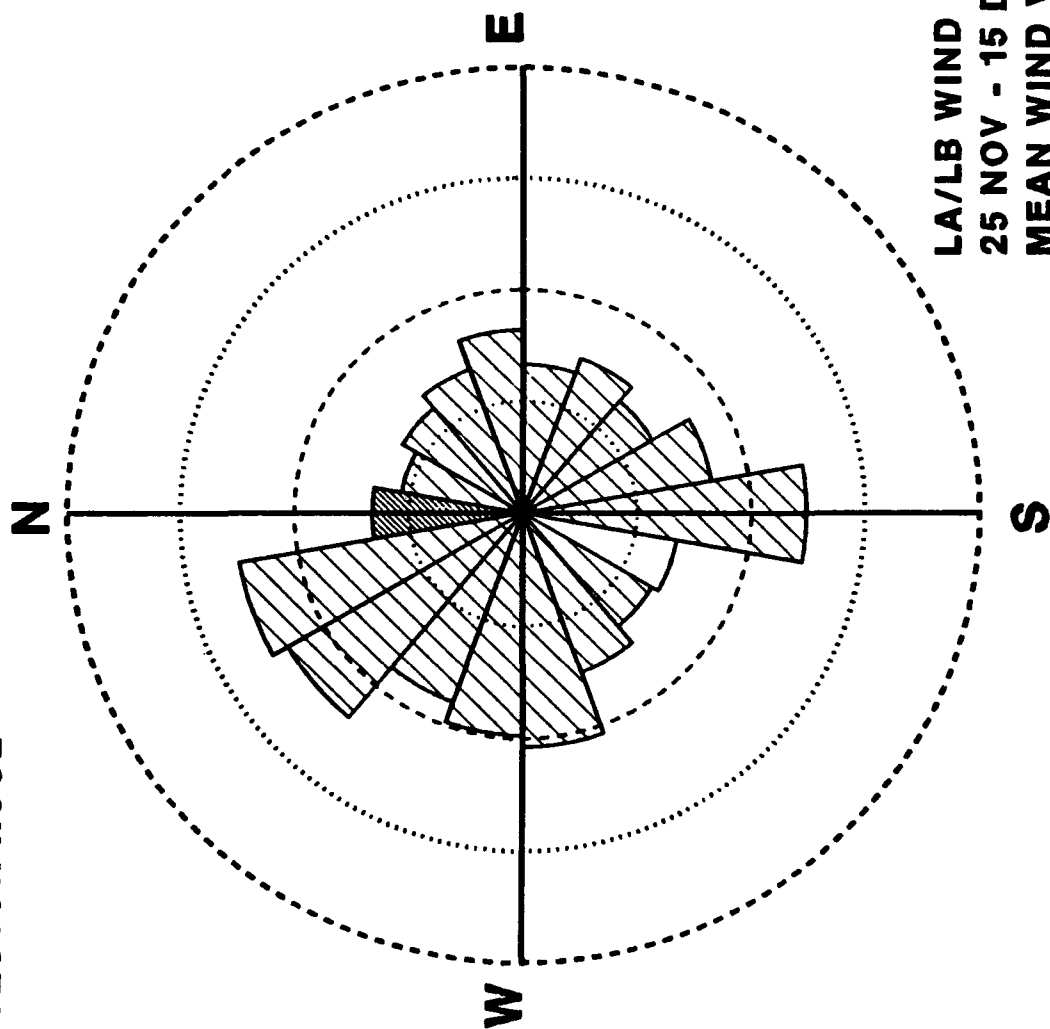
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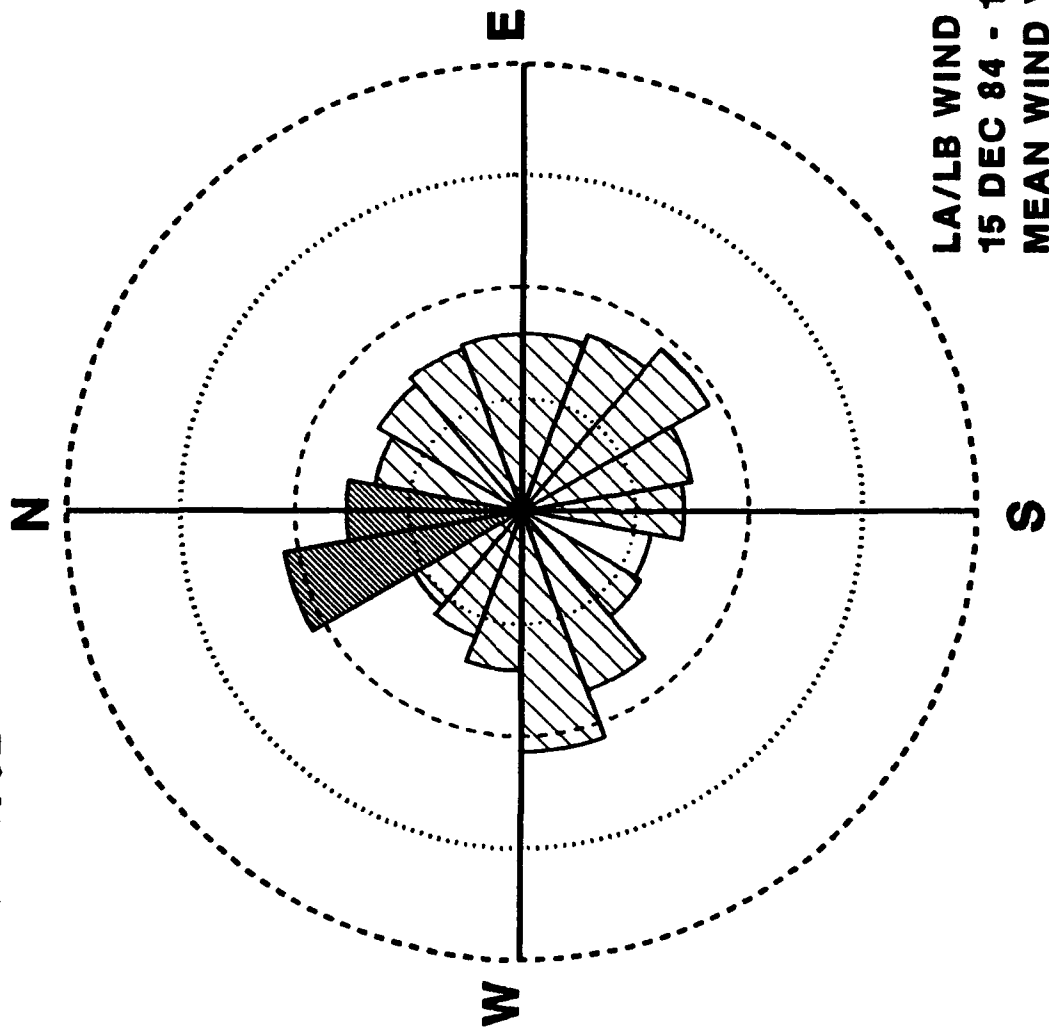
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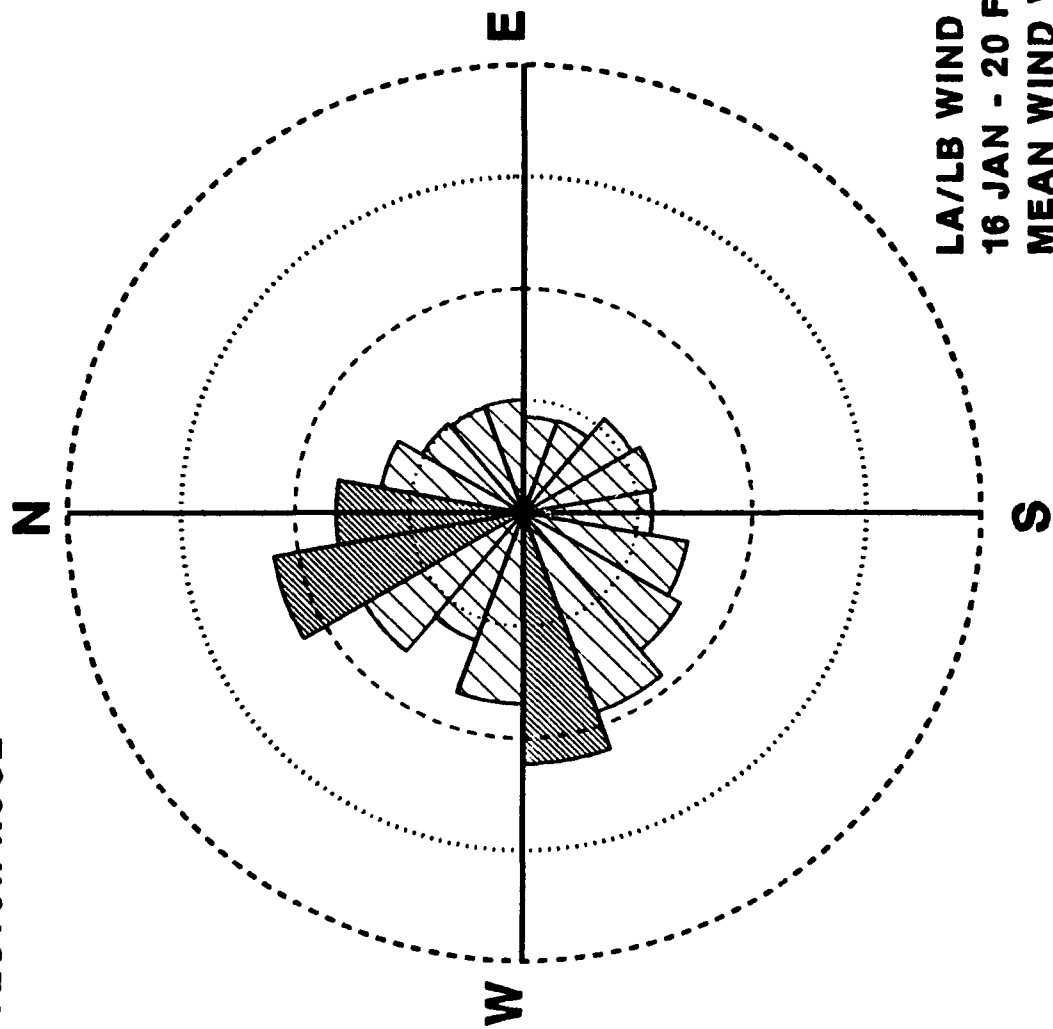
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WIND VECTOR ROSE

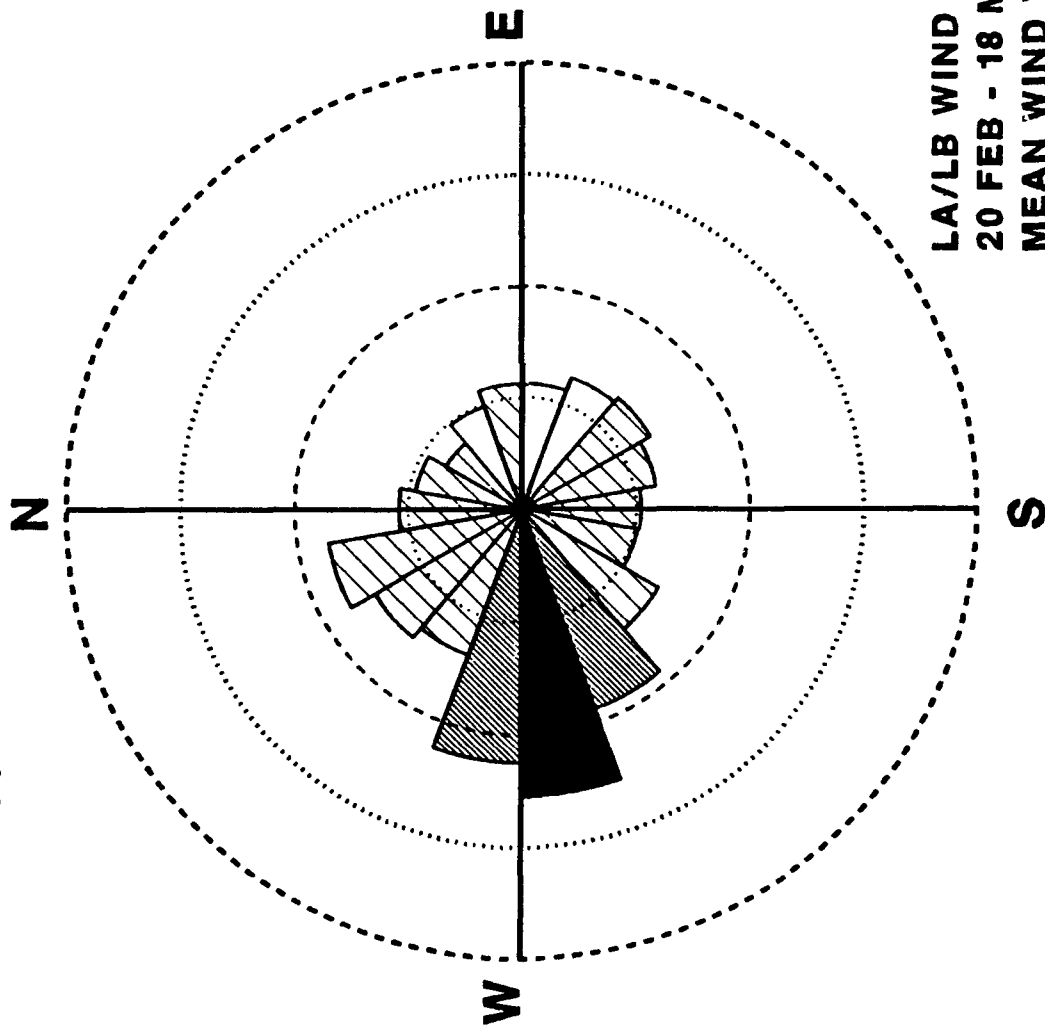


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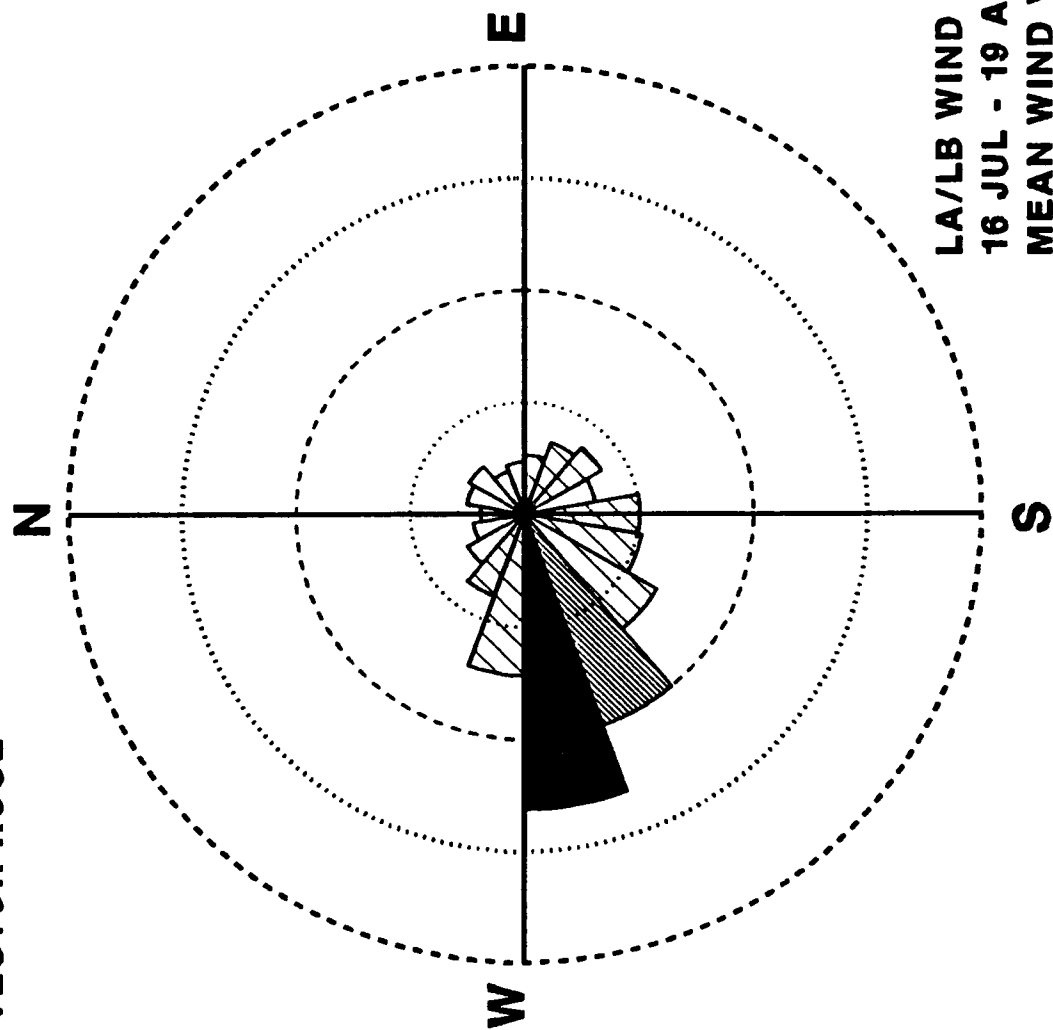
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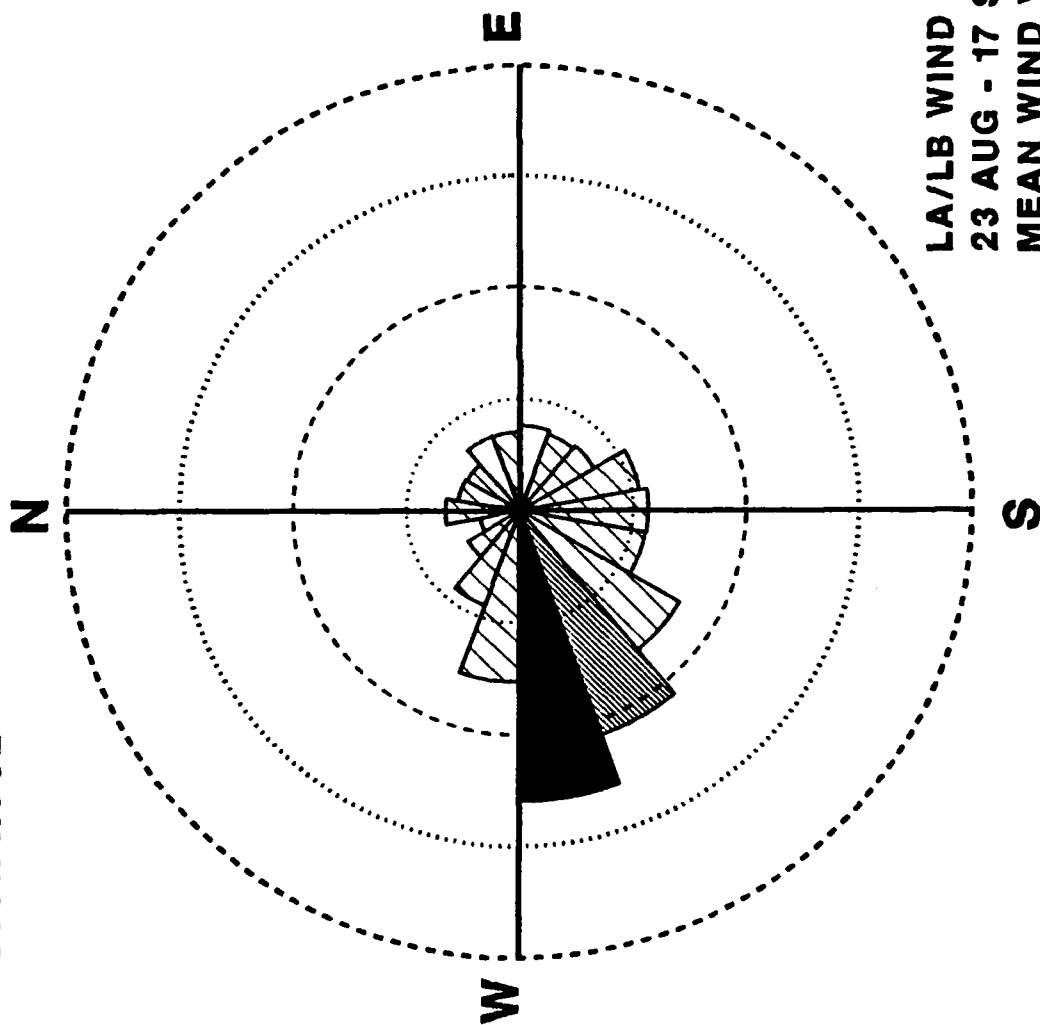


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MEAN WIND VELOCITY

WIND VECTOR ROSE



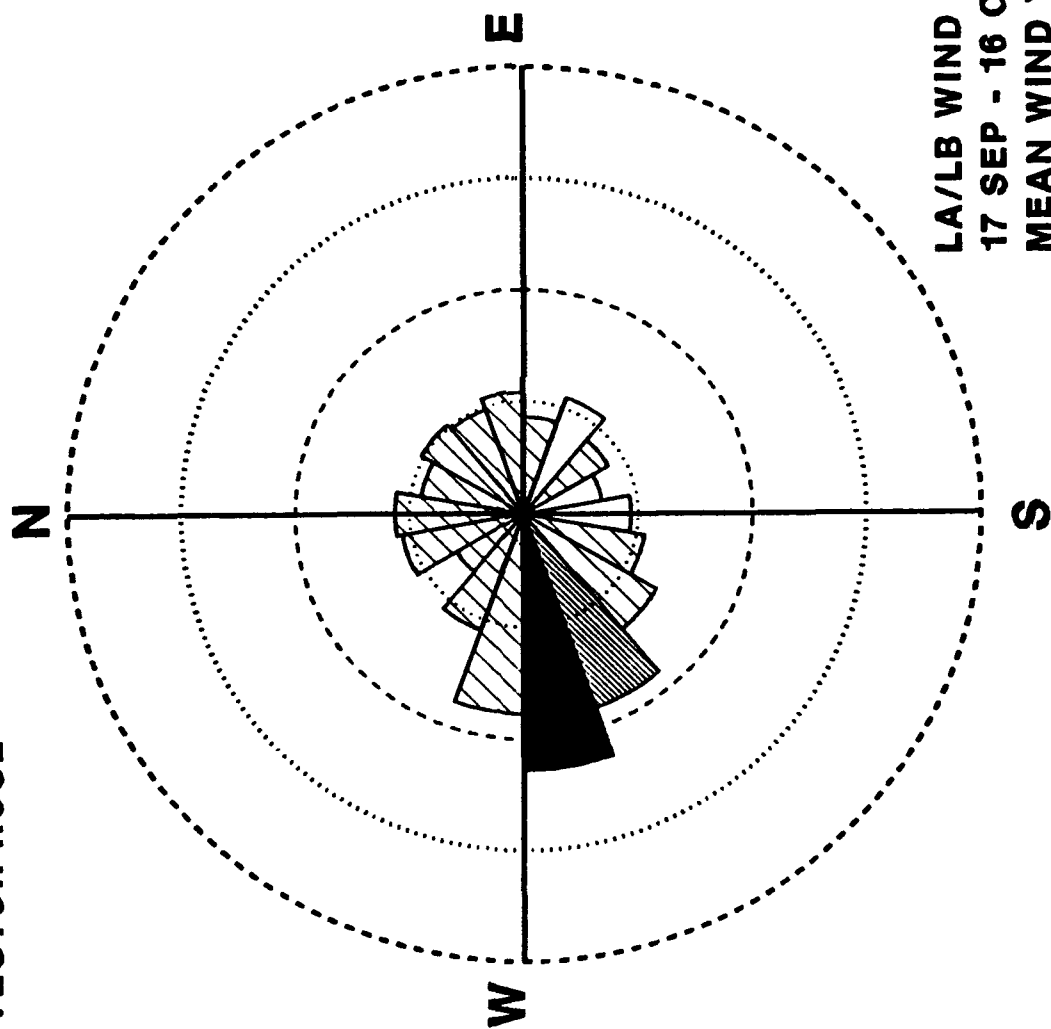
WIND VECTOR ROSE



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 10.0 MPH
 15.0 MPH
 20.0 MPH
PERCENTAGE OF SAMPLES
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 2-10%
 10-20%
 ≥ 20%

LA/LB WIND STUDY
23 AUG - 17 SEP 1985
MEAN WIND VELOCITY

WIND VECTOR ROSE



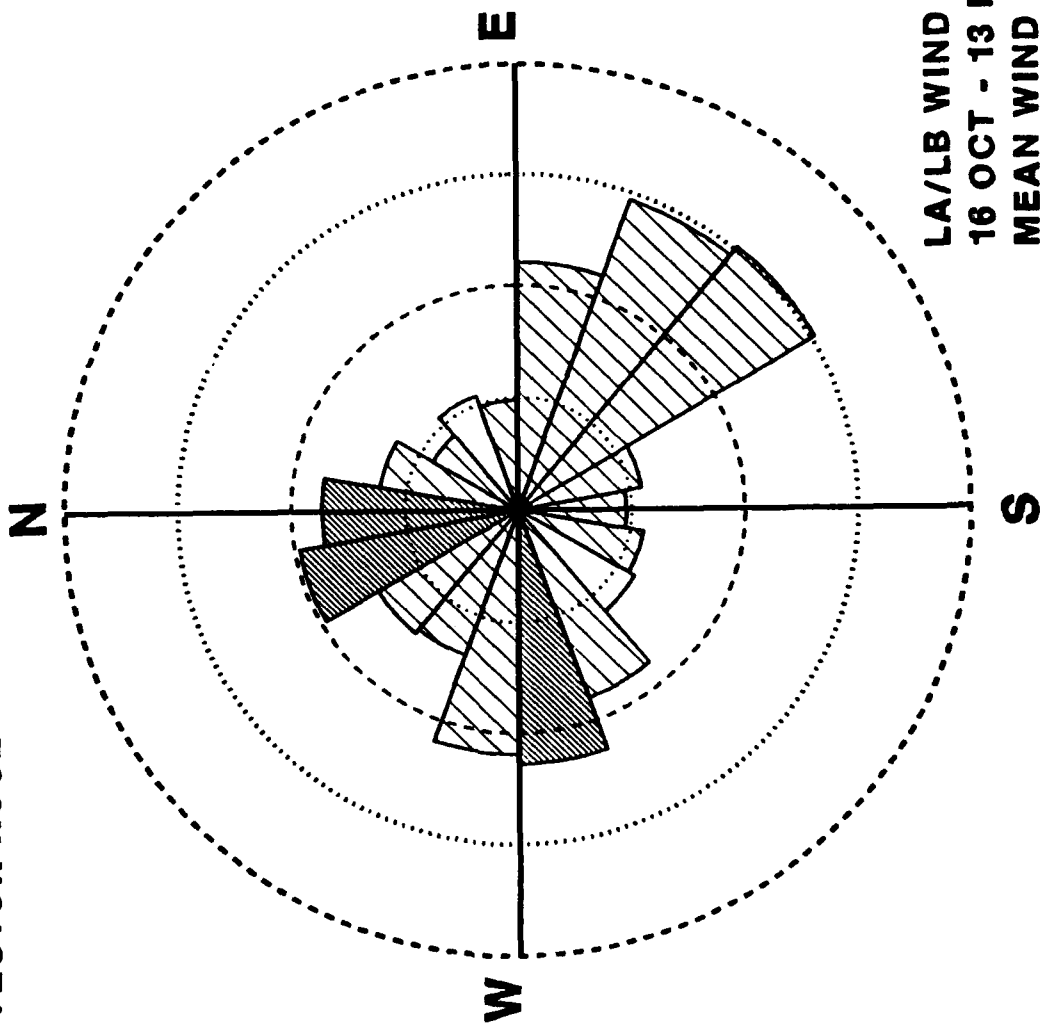
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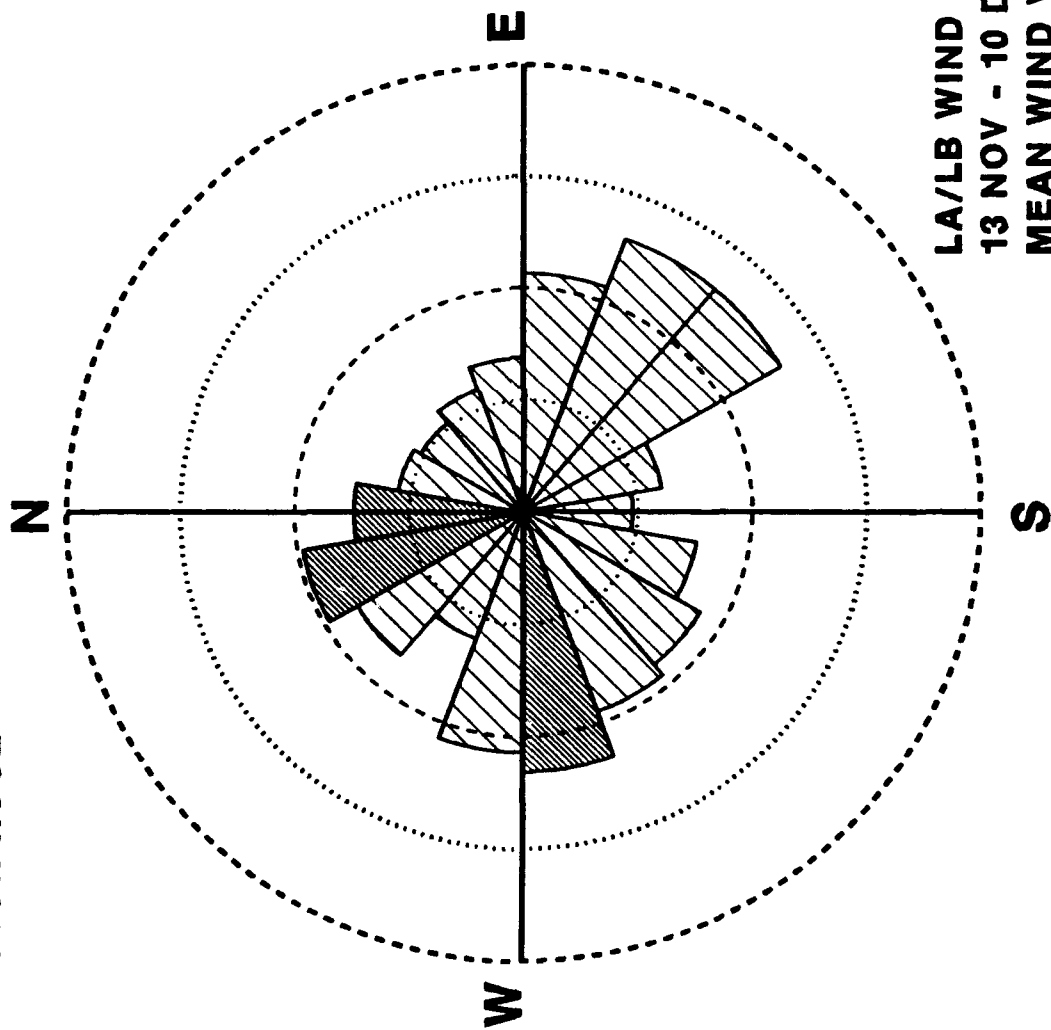
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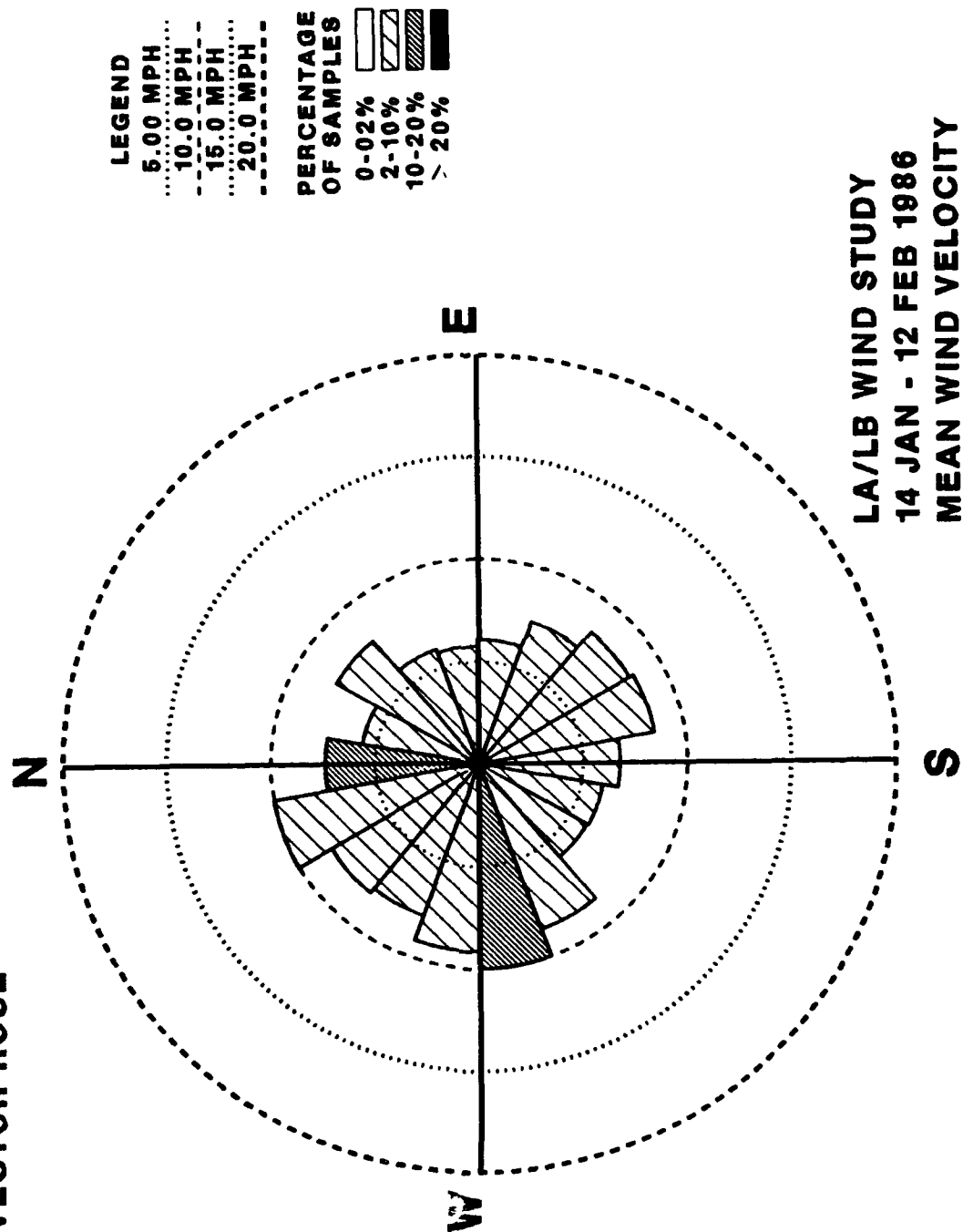
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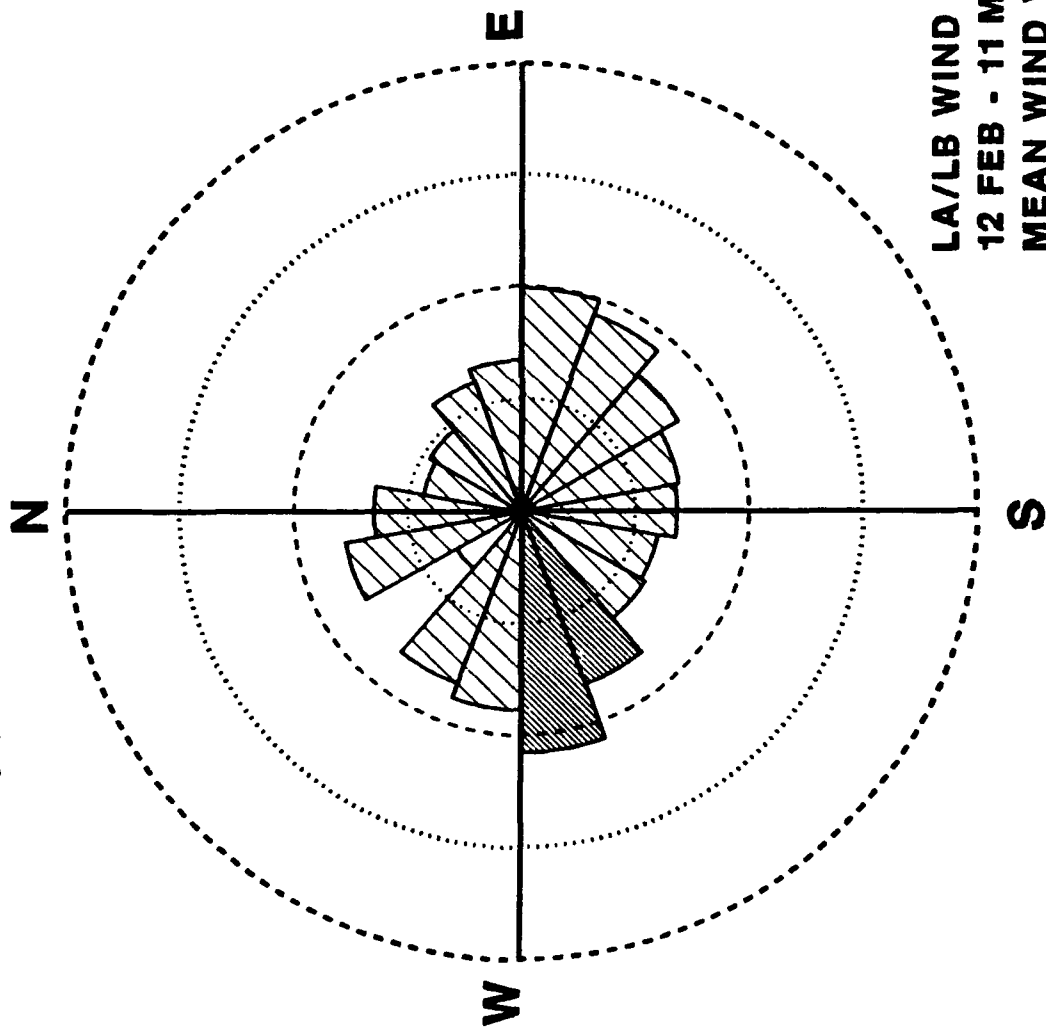
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WIND VECTOR ROSE

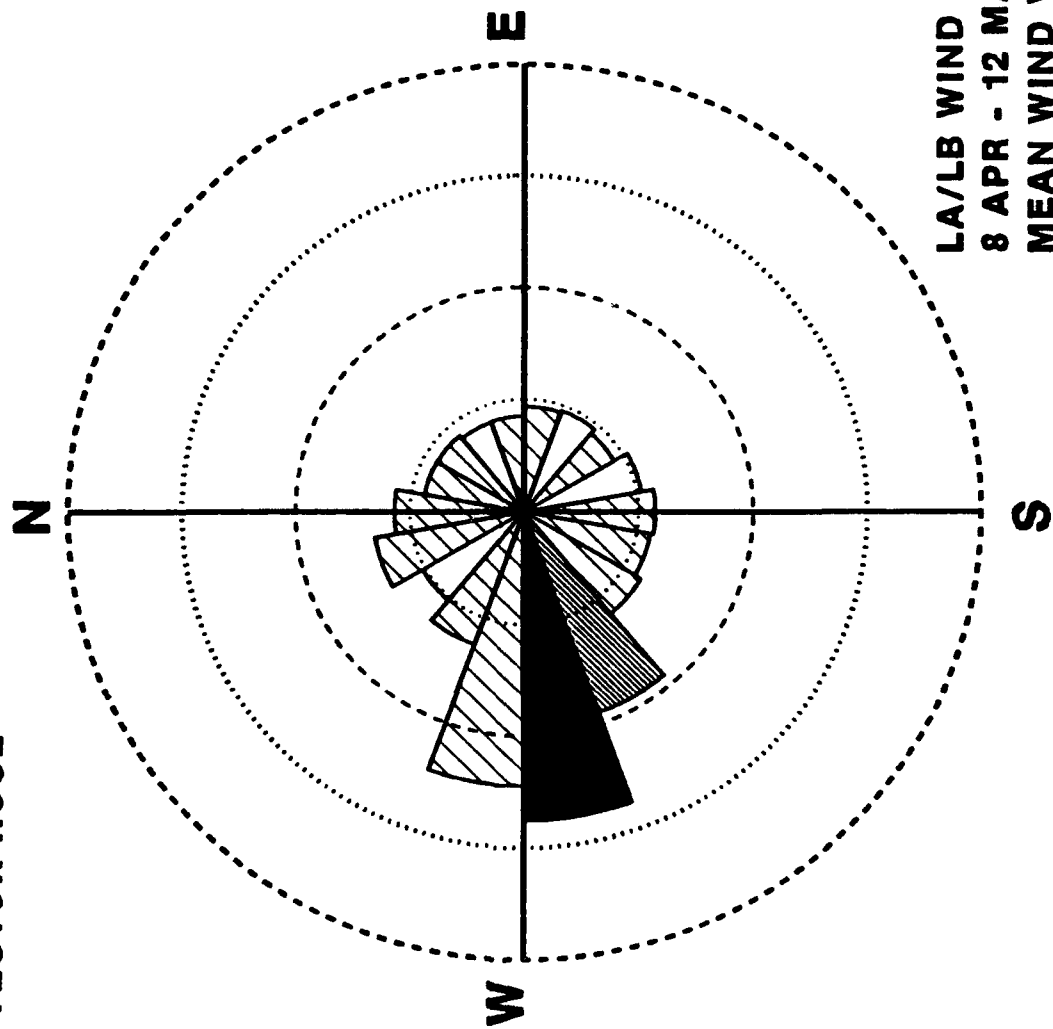


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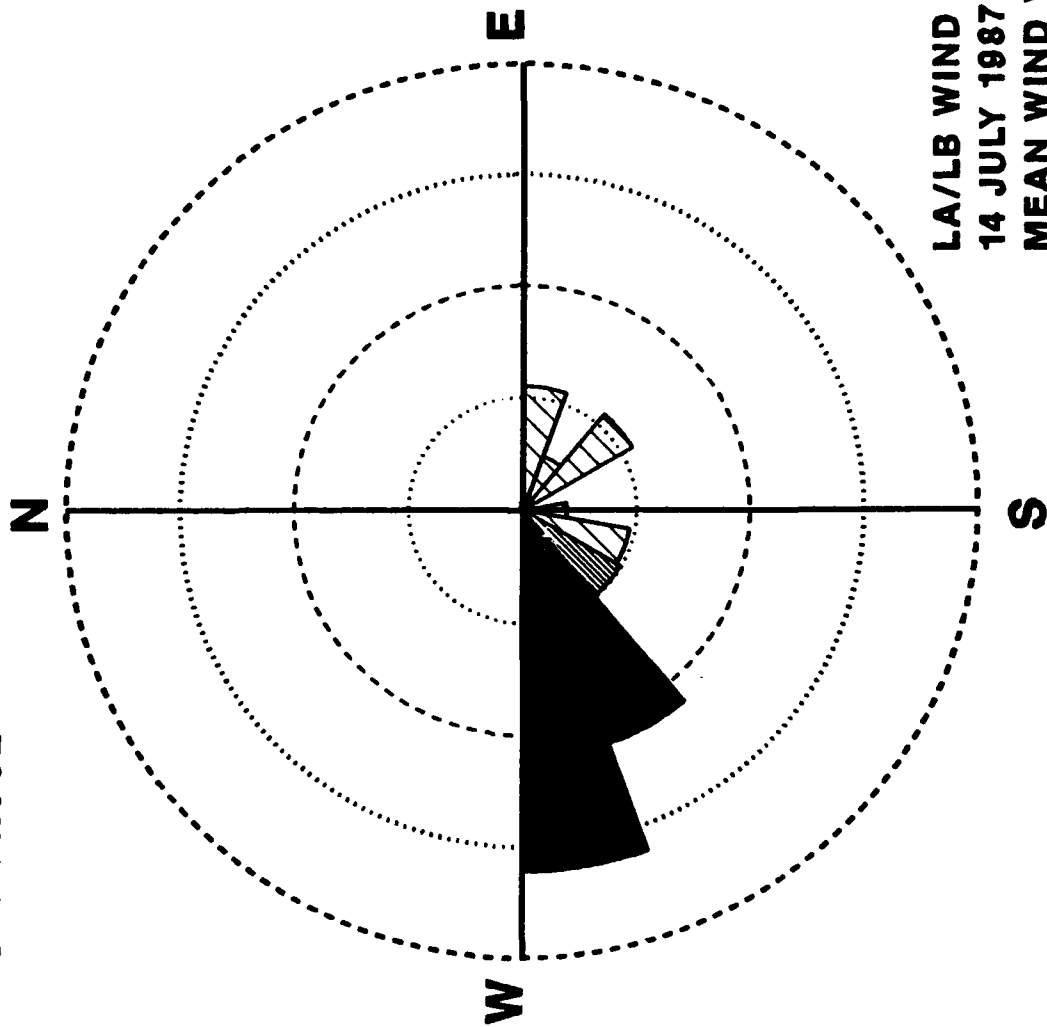
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WIND VECTOR ROSE



LA/LB WIND STUDY
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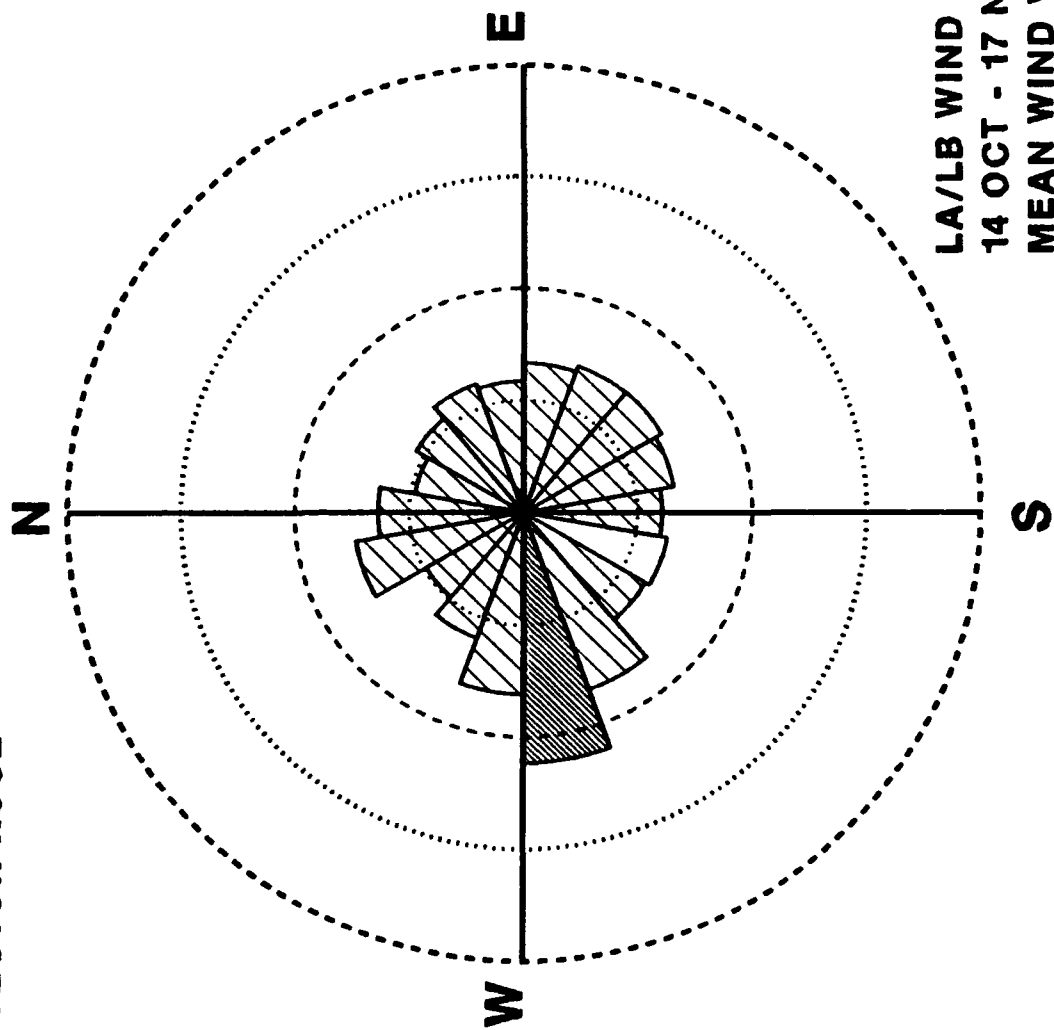
WIND VECTOR ROSE



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PERCENTAGE OF SAMPLES
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 10-20%
 > 20%

LA/LB WIND STUDY
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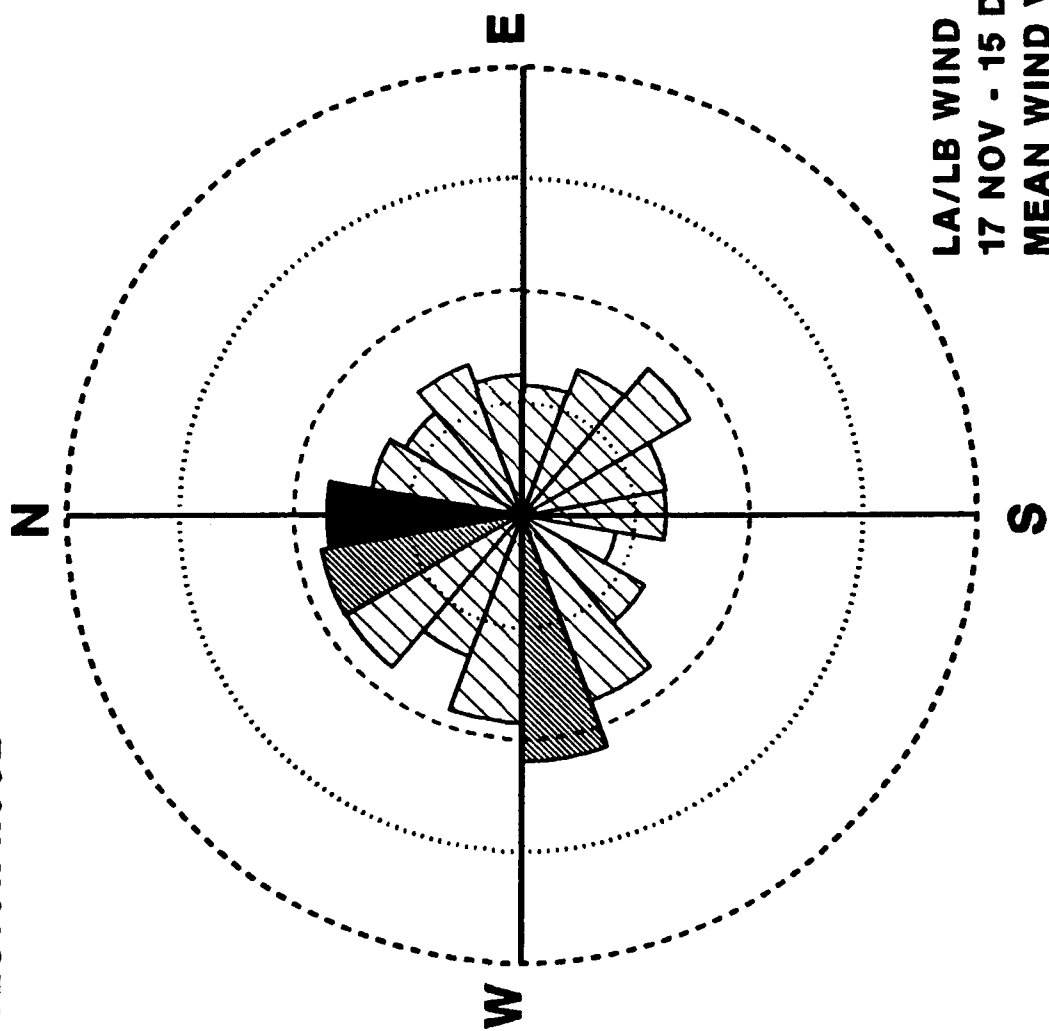
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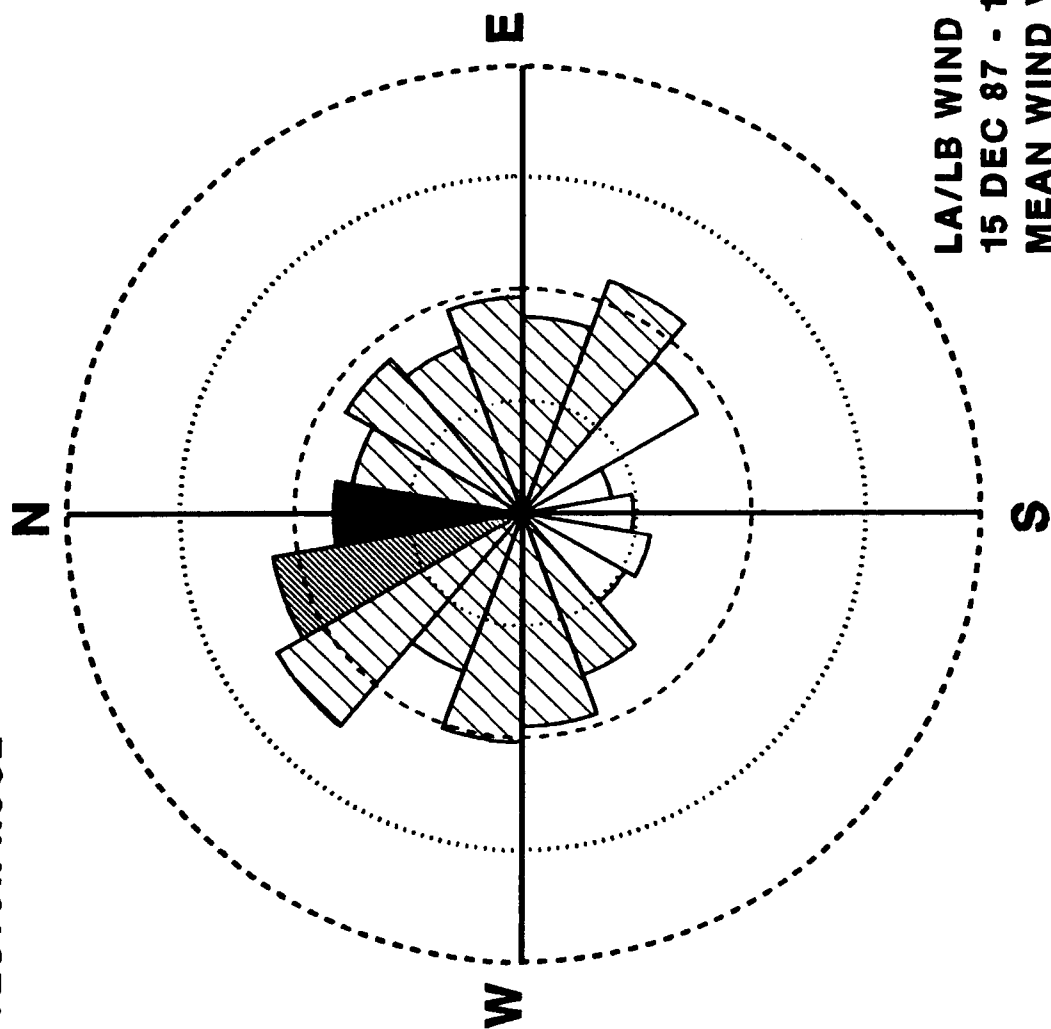
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LA/LB WIND STUDY
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MEAN WIND VELOCITY

WIND VECTOR ROSE



WIND VECTOR ROSE



LEGEND

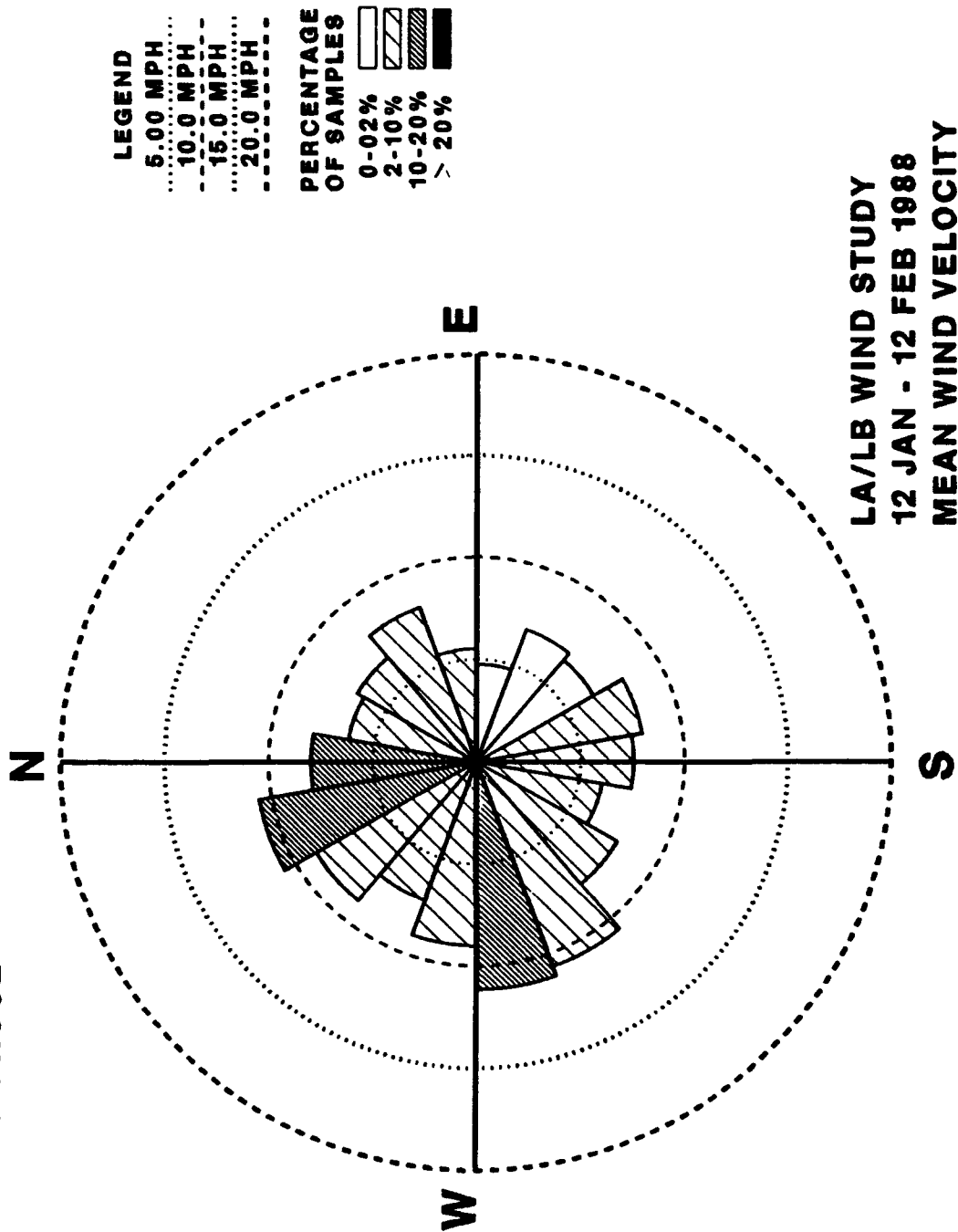
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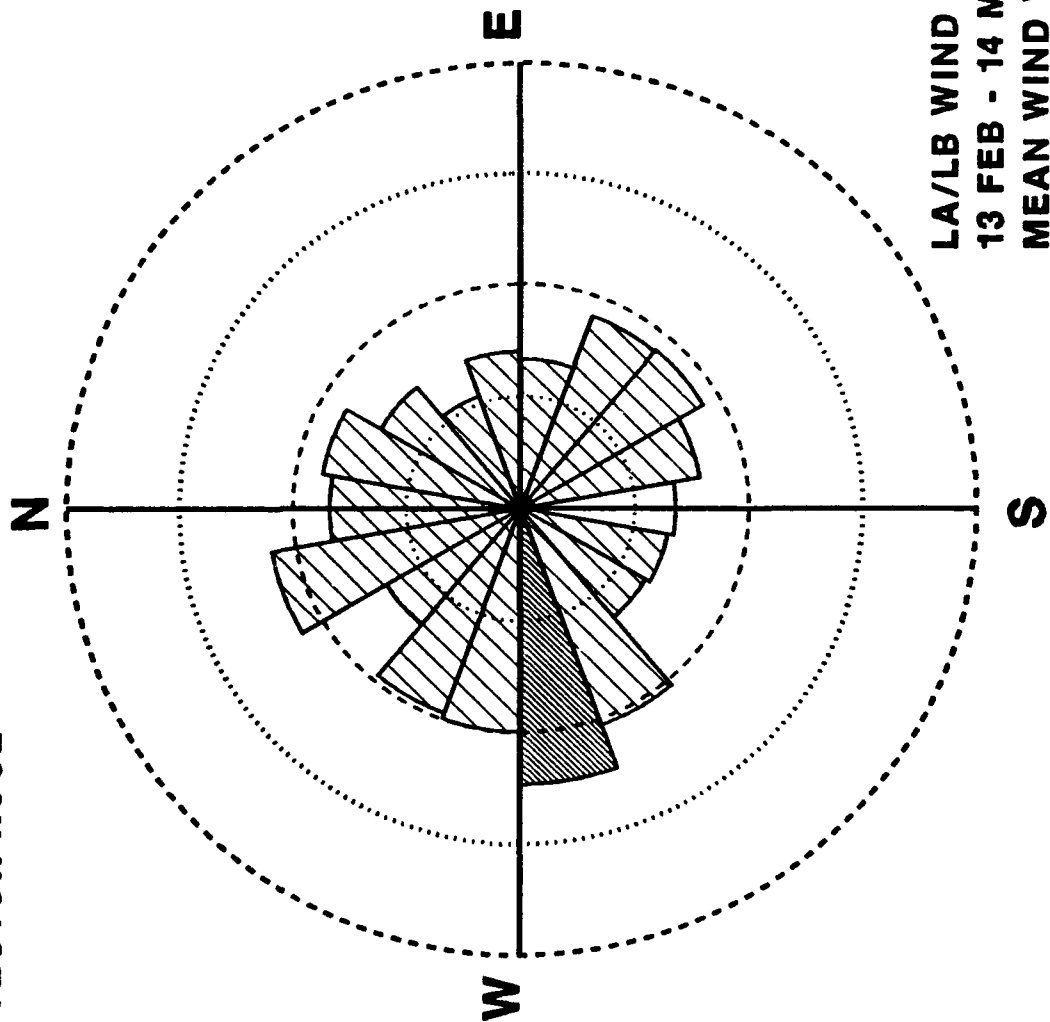
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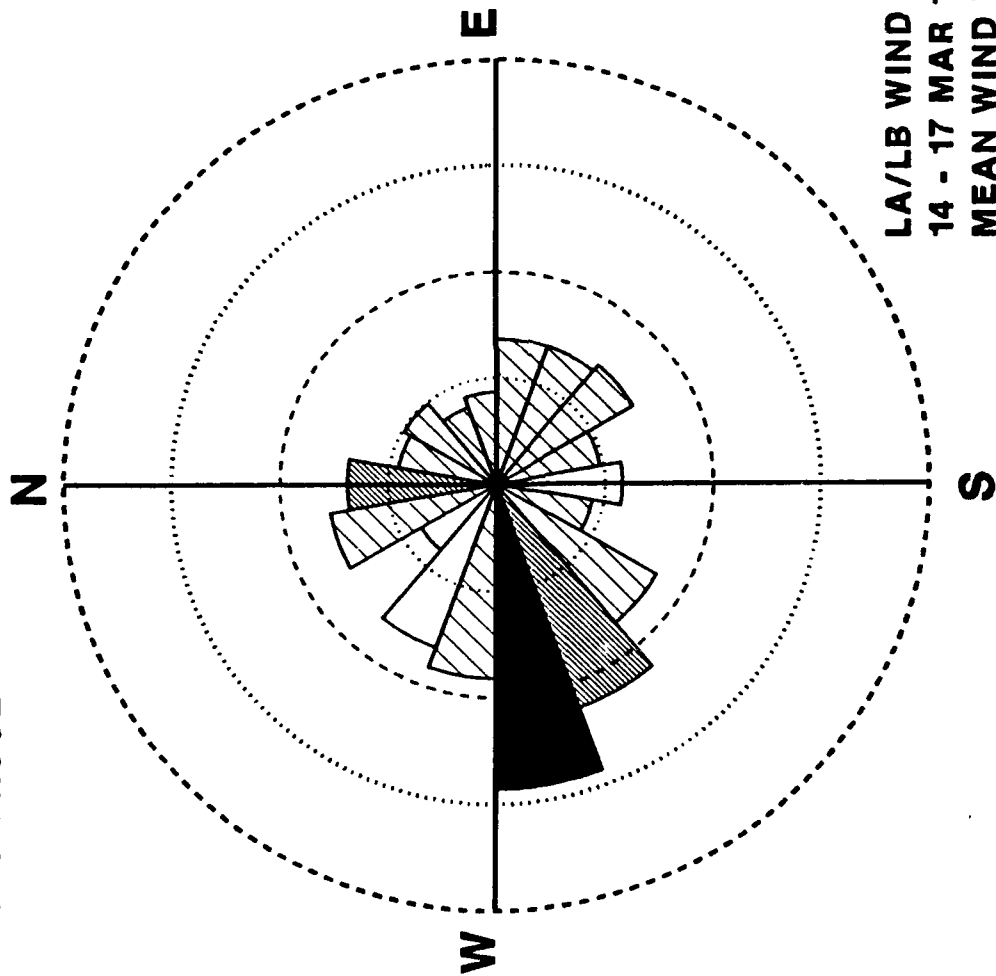
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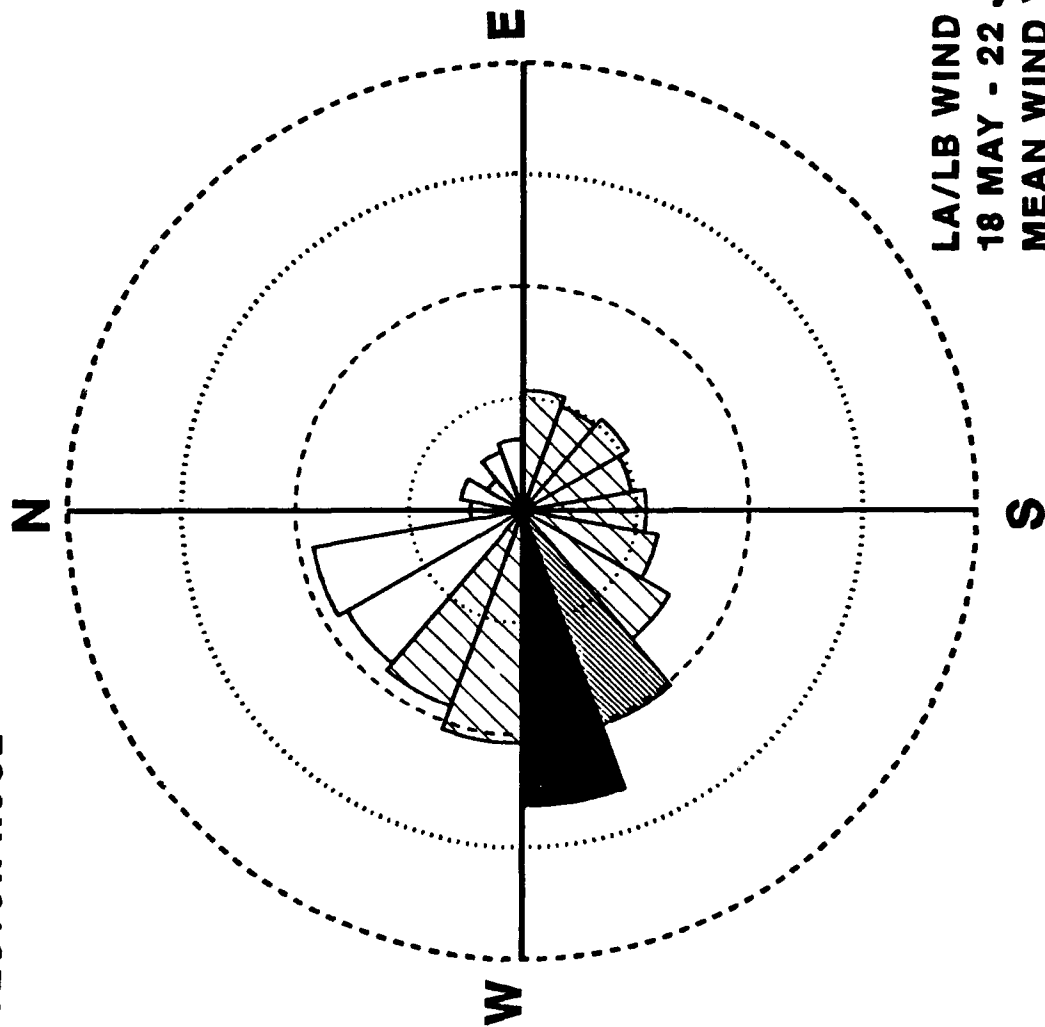
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WIND VECTOR ROSE



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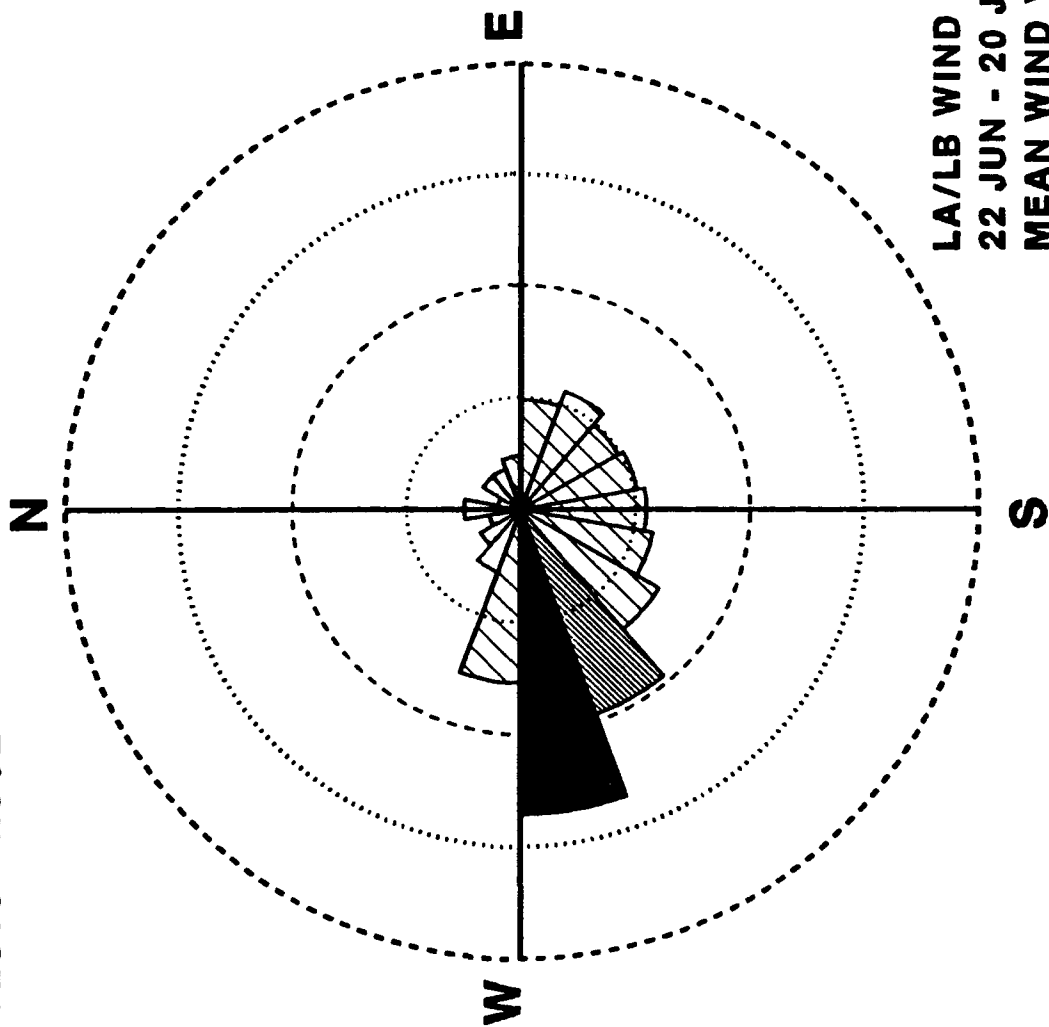


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 20.0 MPH

PERCENTAGE OF SAMPLES
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 10-20%
 > 20%

LA/LB WIND STUDY
18 MAY - 22 JUN 1988
MEAN WIND VELOCITY

WIND VECTOR ROSE

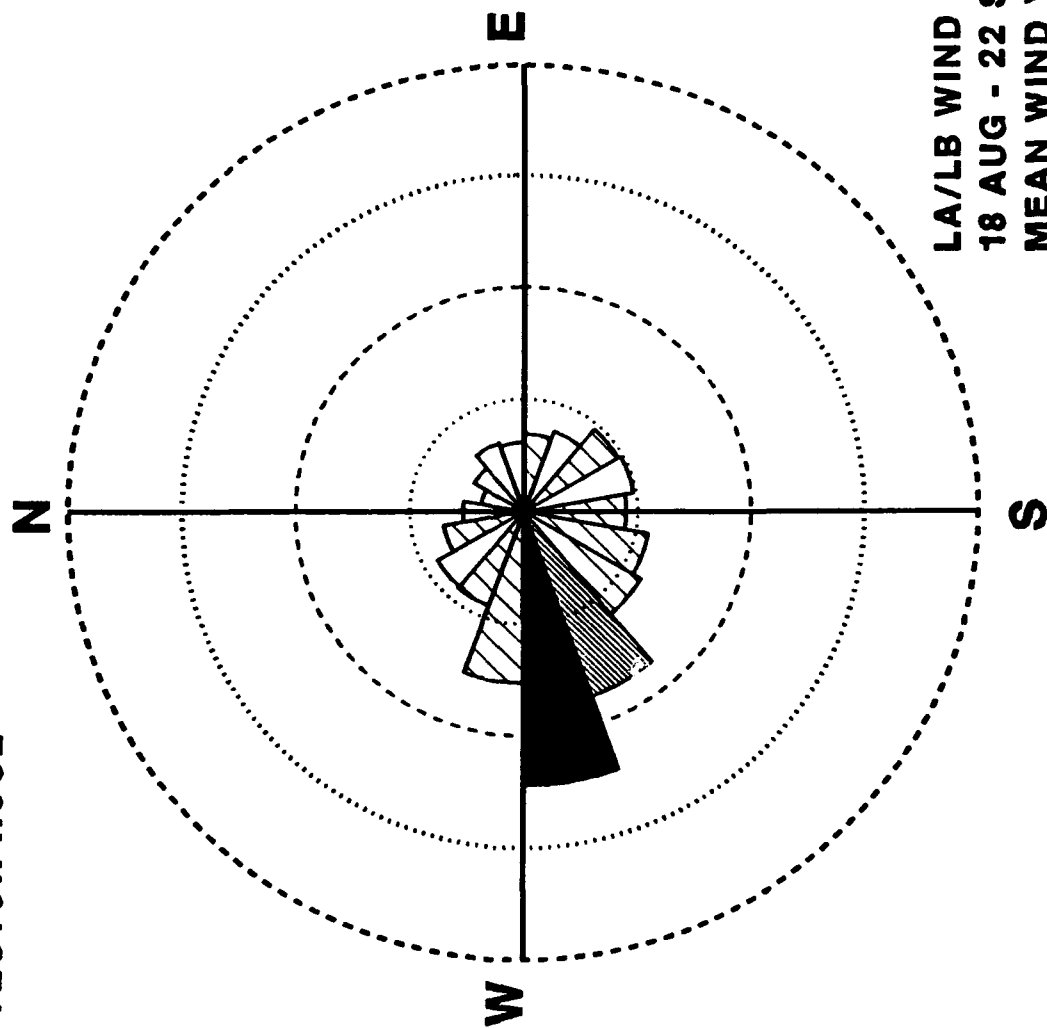


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PERCENTAGE OF SAMPLES
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LA/LB WIND STUDY
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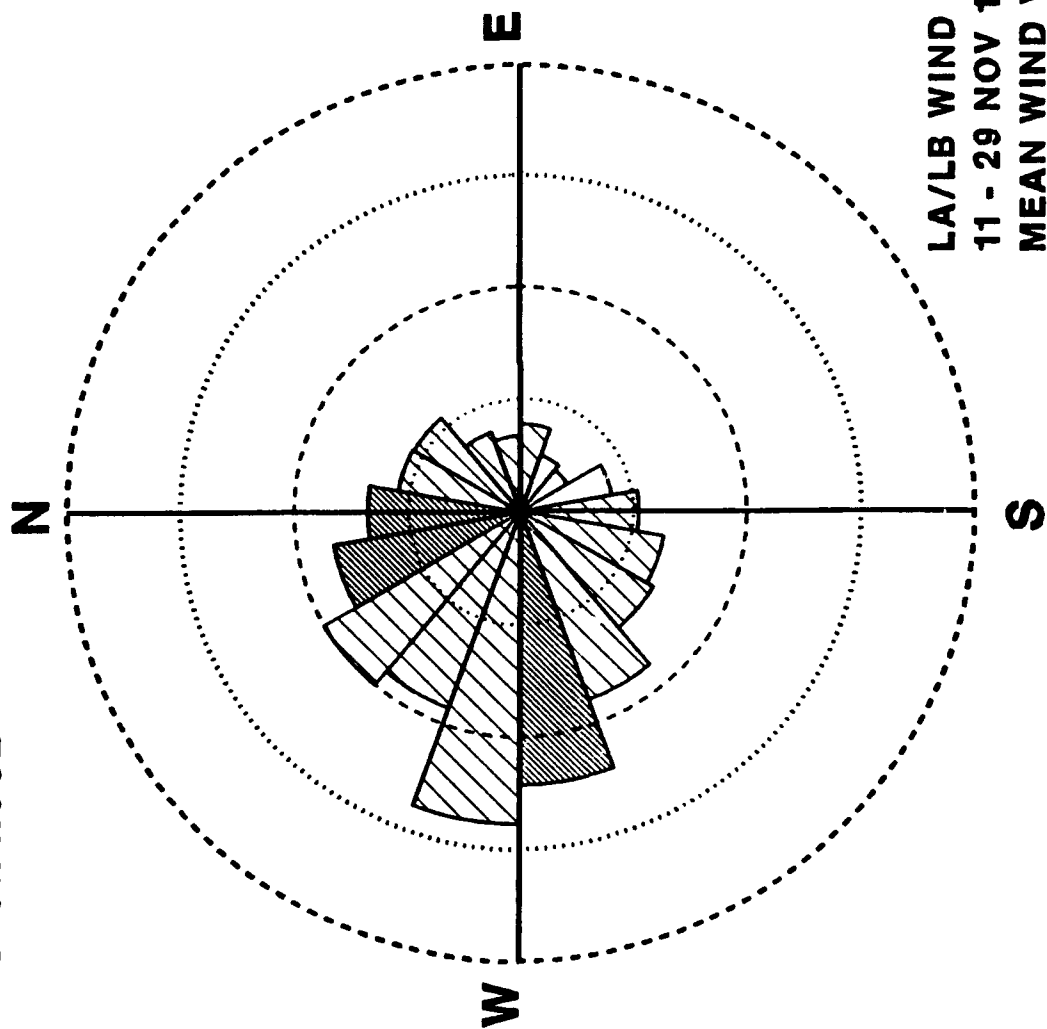
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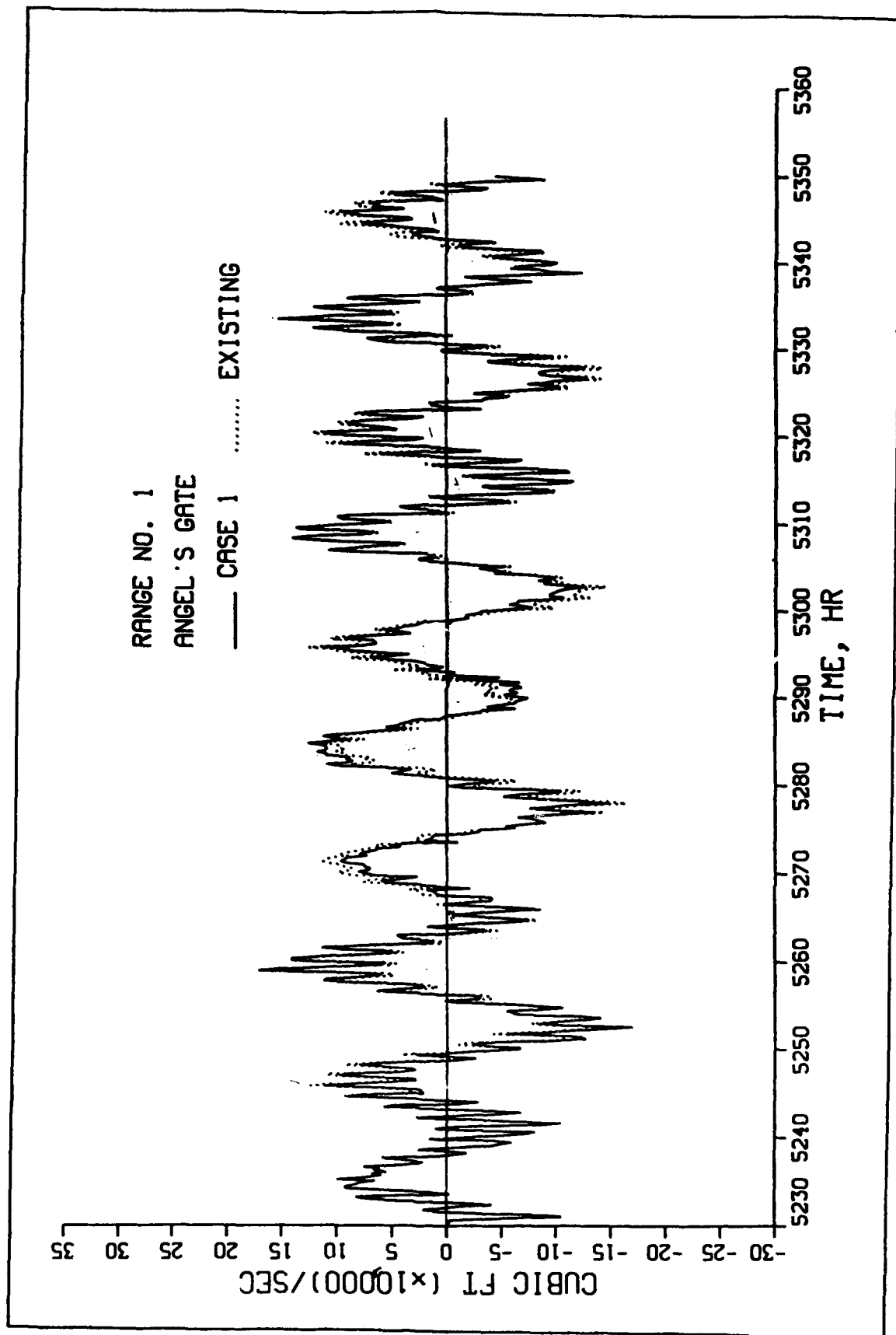


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LA/LB WIND STUDY
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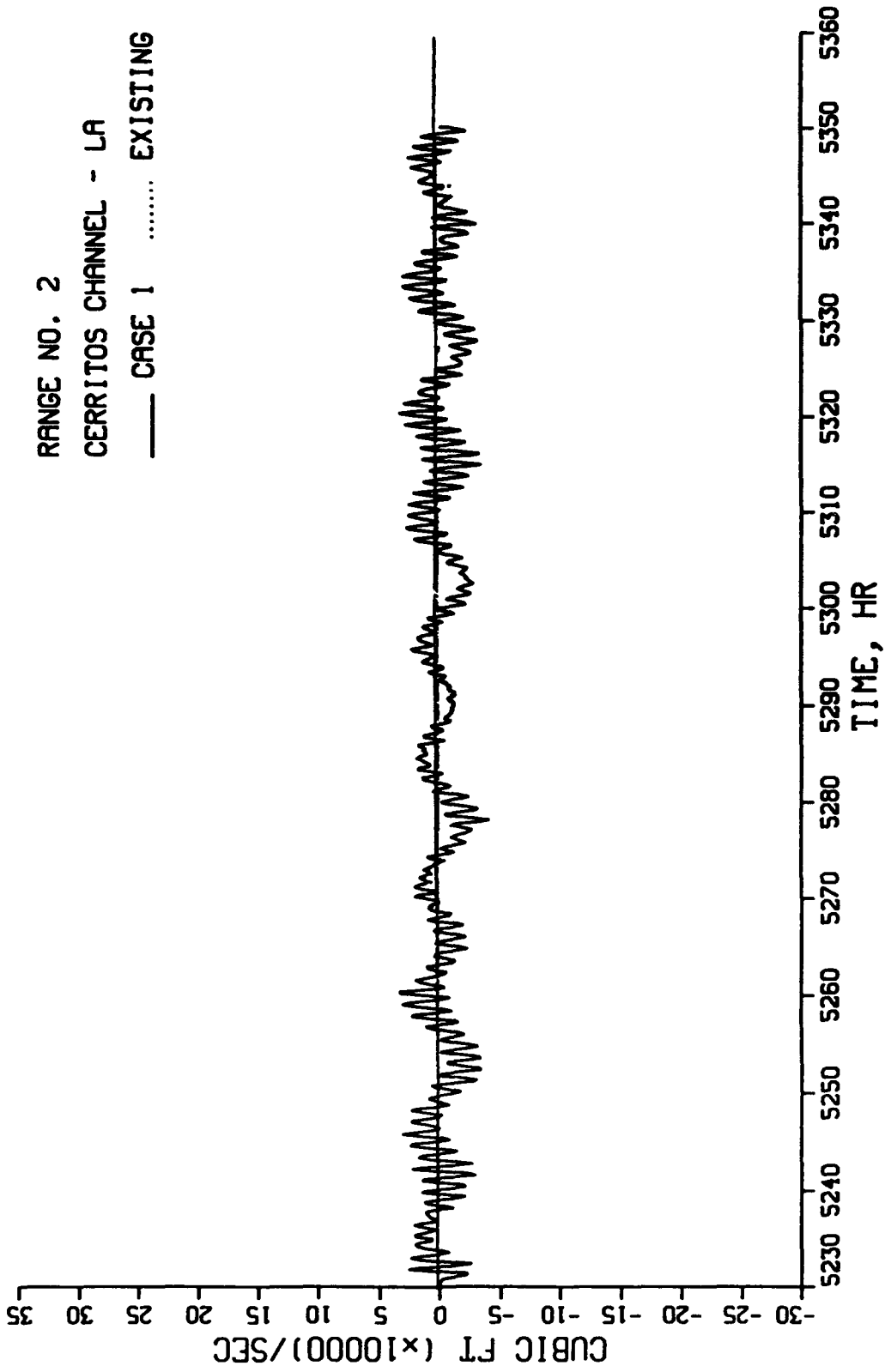
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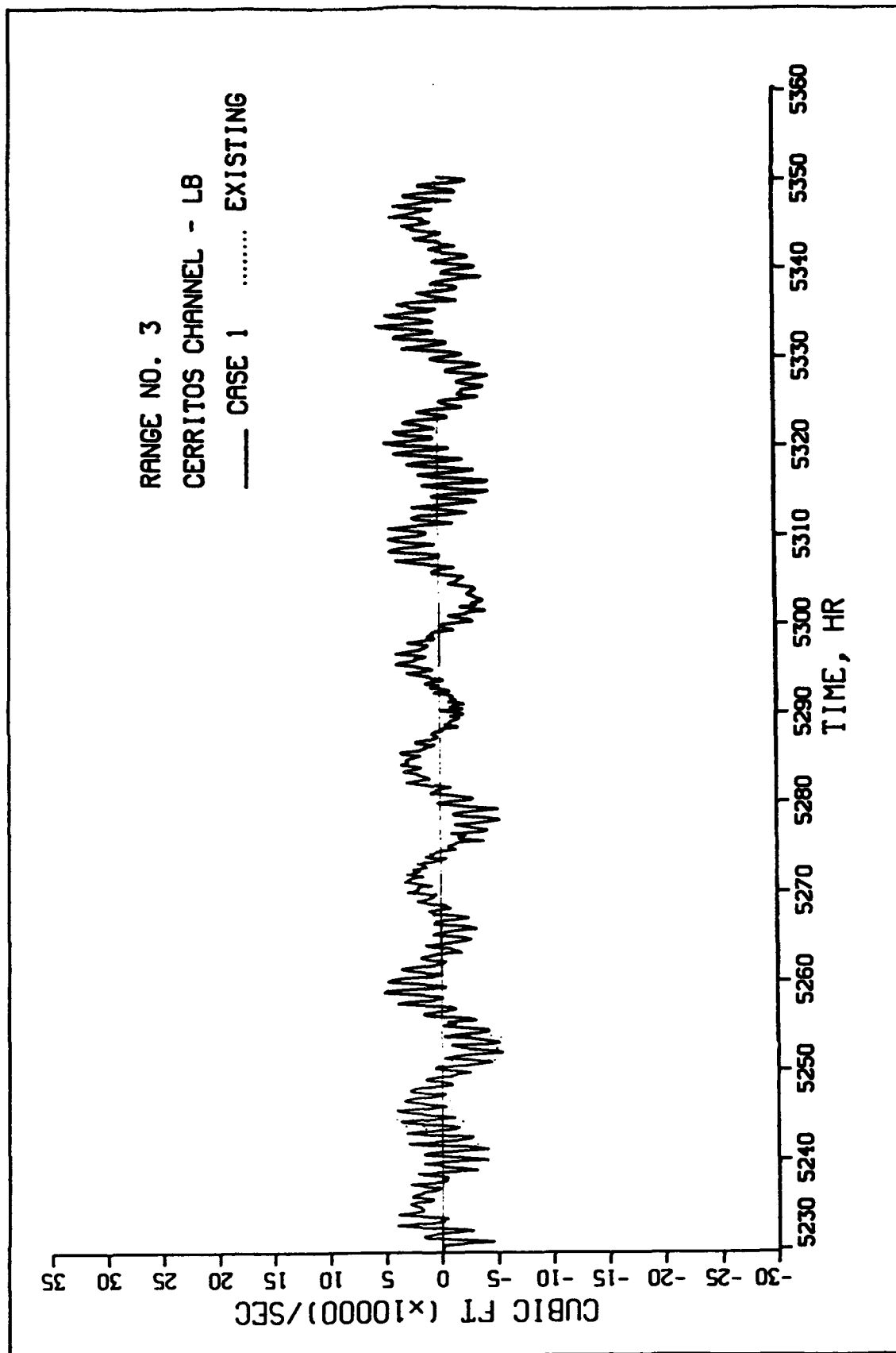




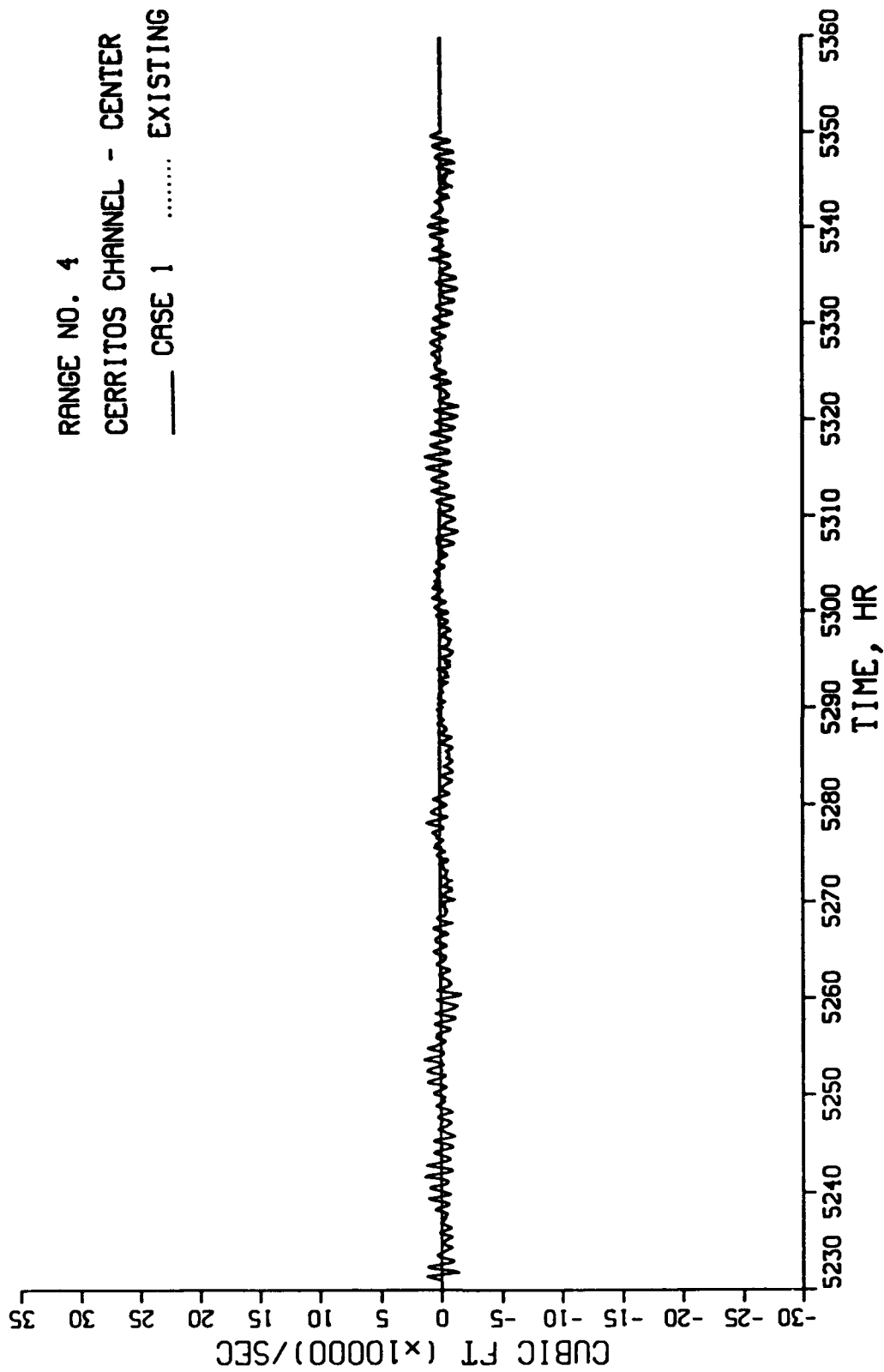
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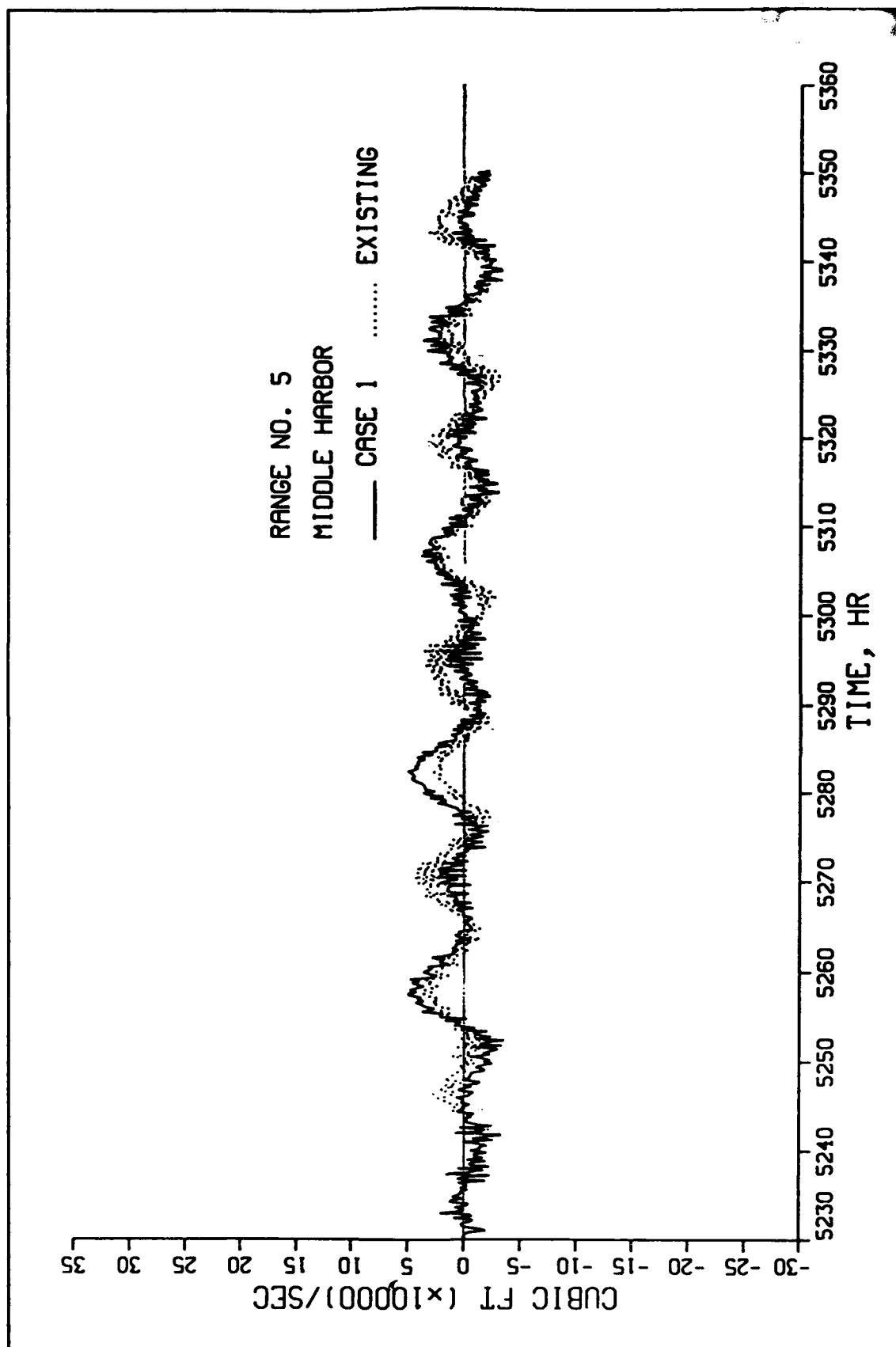
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— CASE 1 EXISTING





RANGE NO. 4
CERRITOS CHANNEL - CENTER
— CASE 1 EXISTING





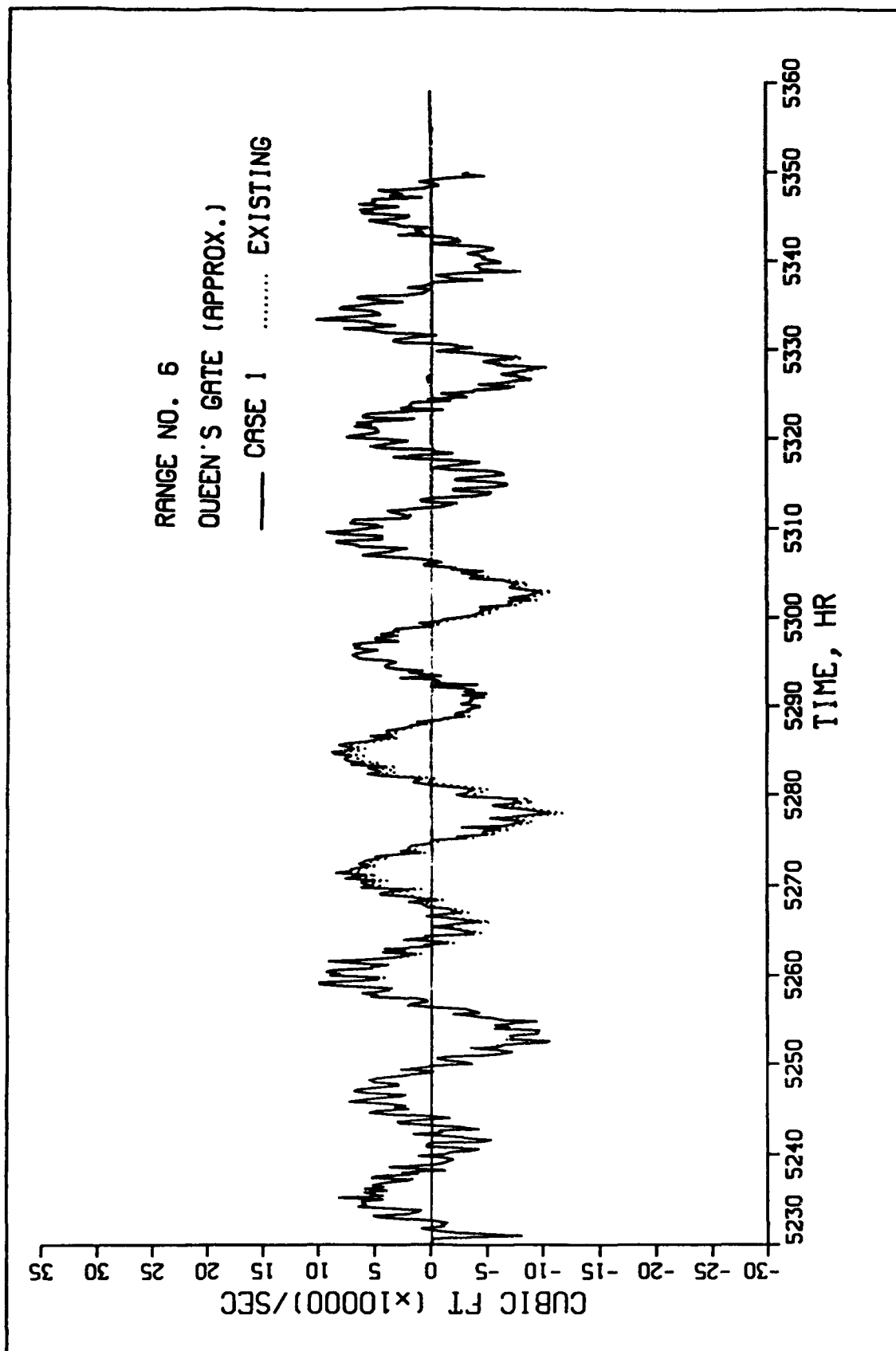
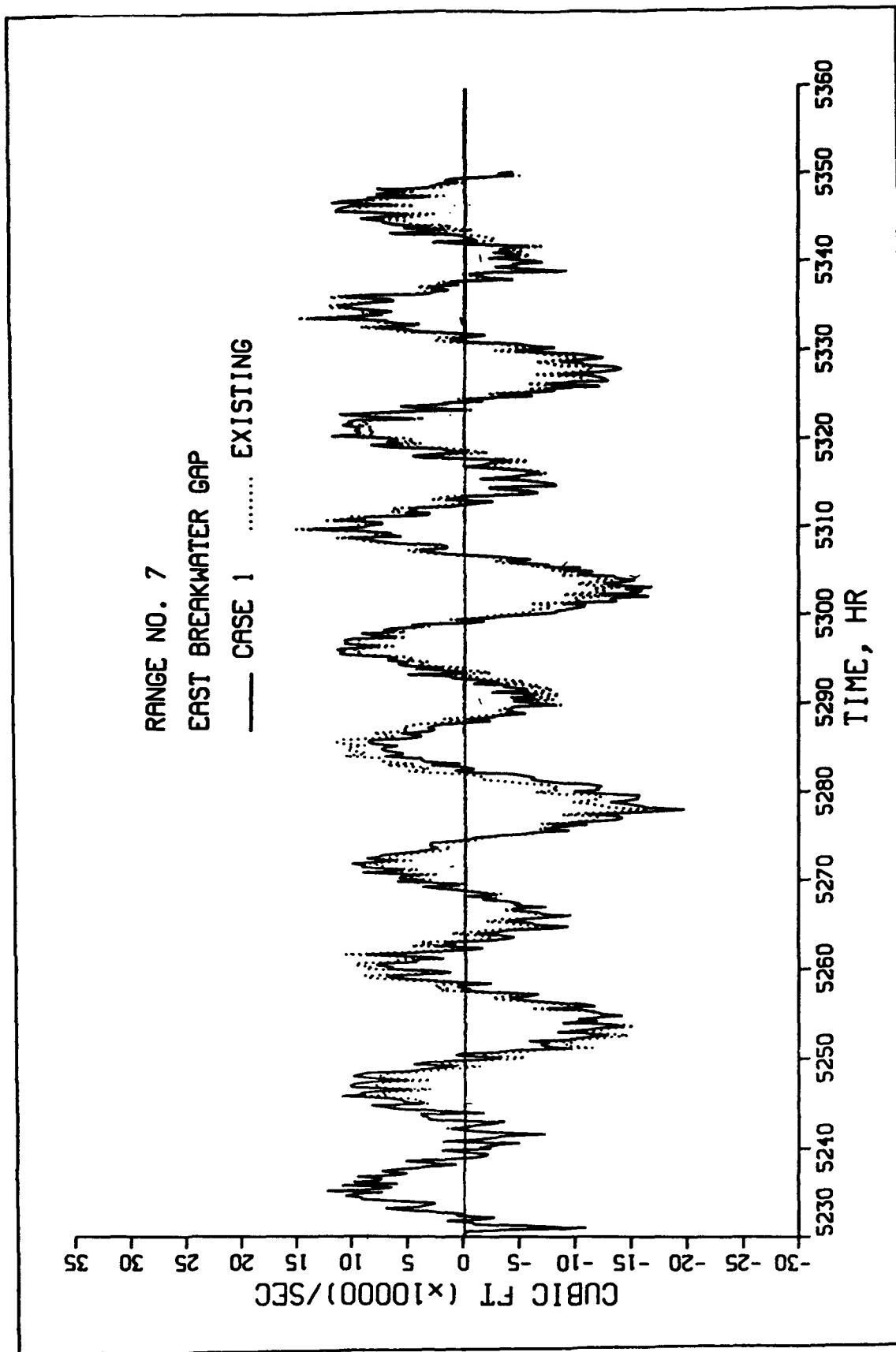
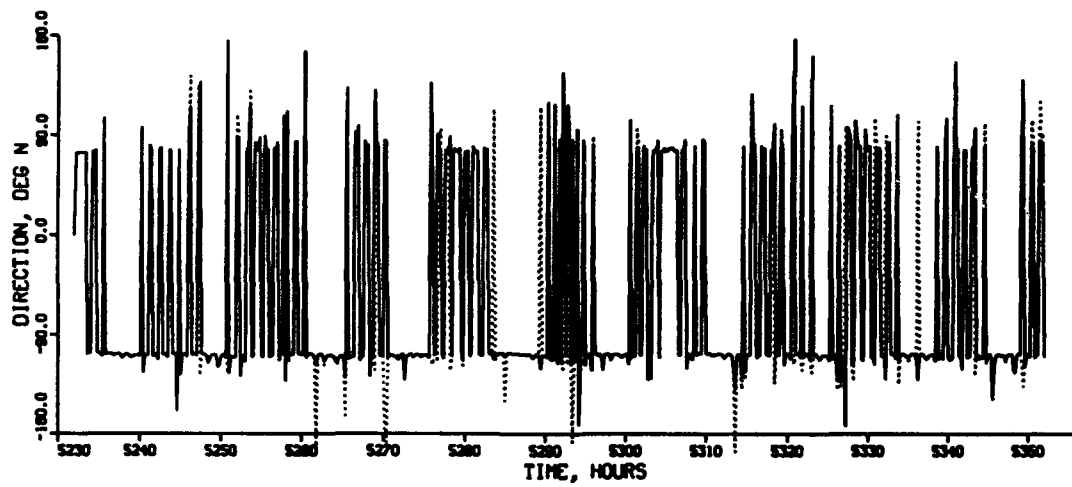
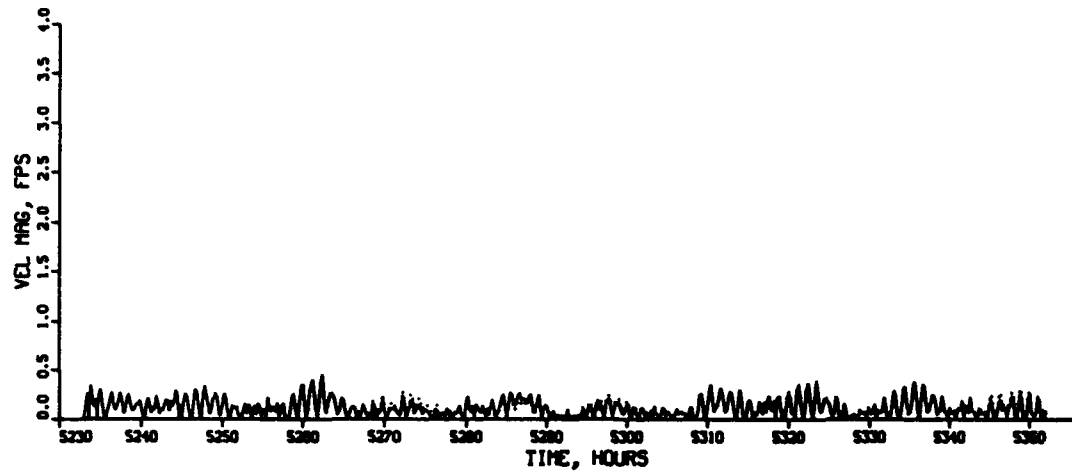


PLATE 32



CASE NO. 1 (46, 80) LAYER NO. 1
— CASE 1 EXISTING



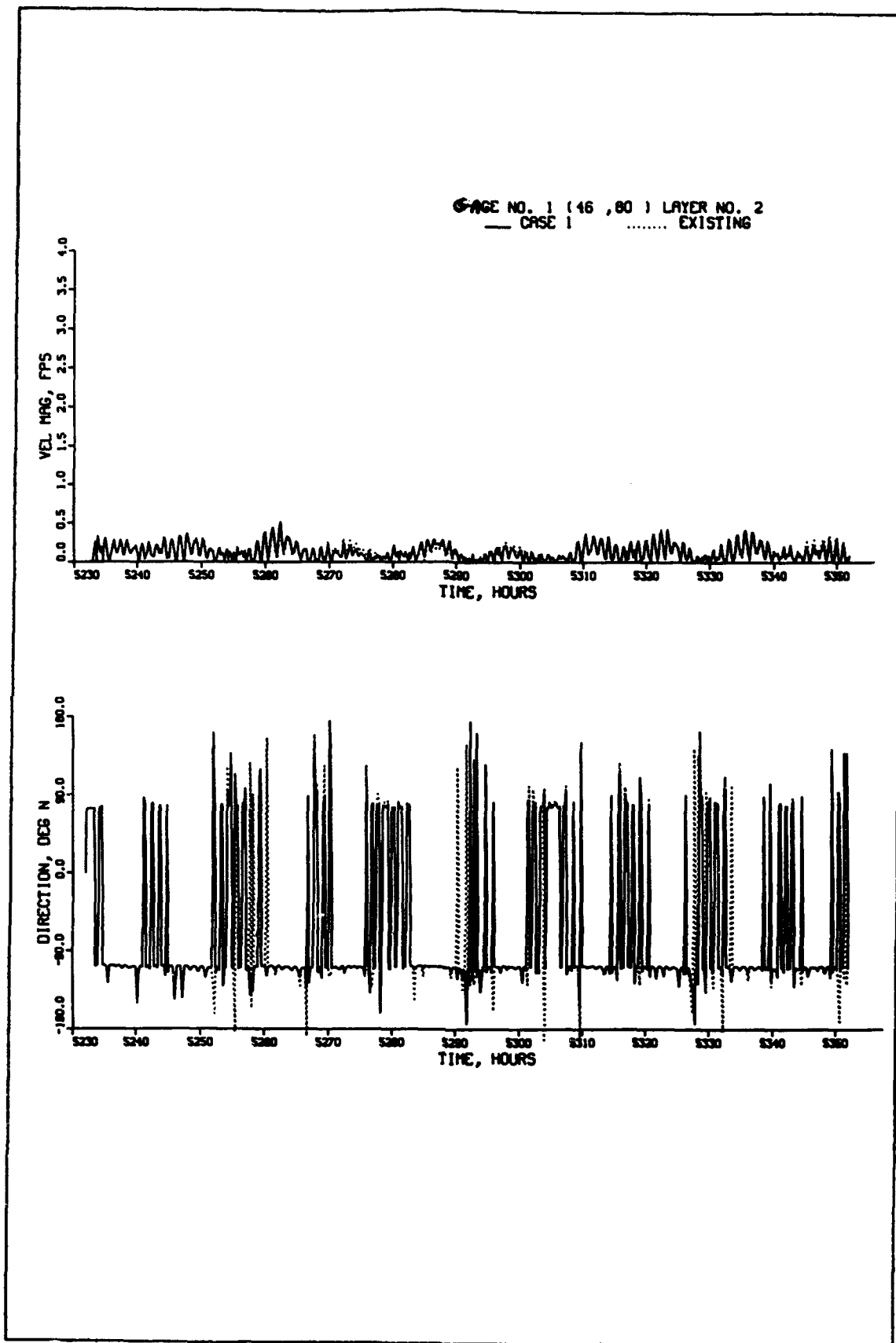
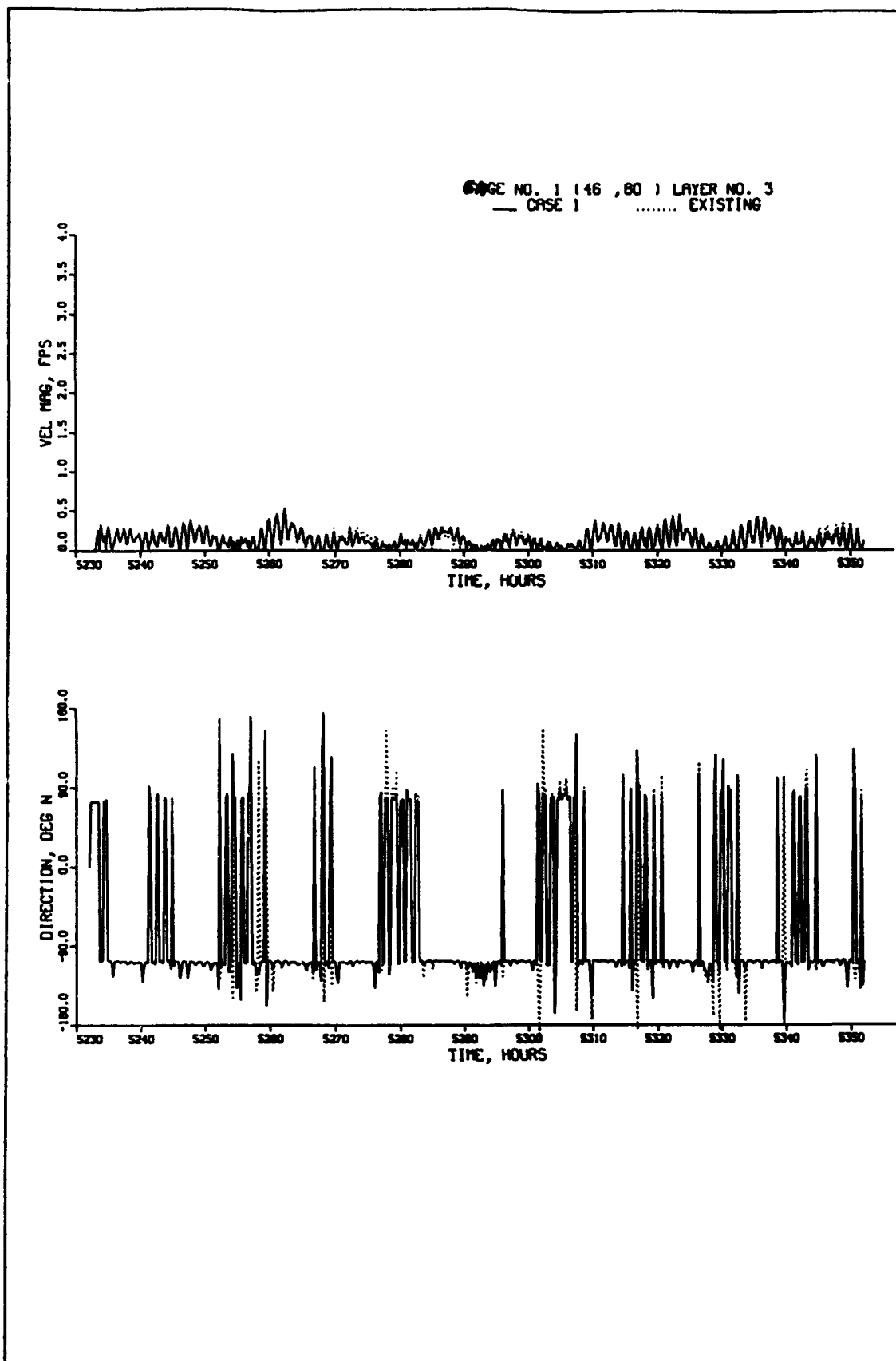
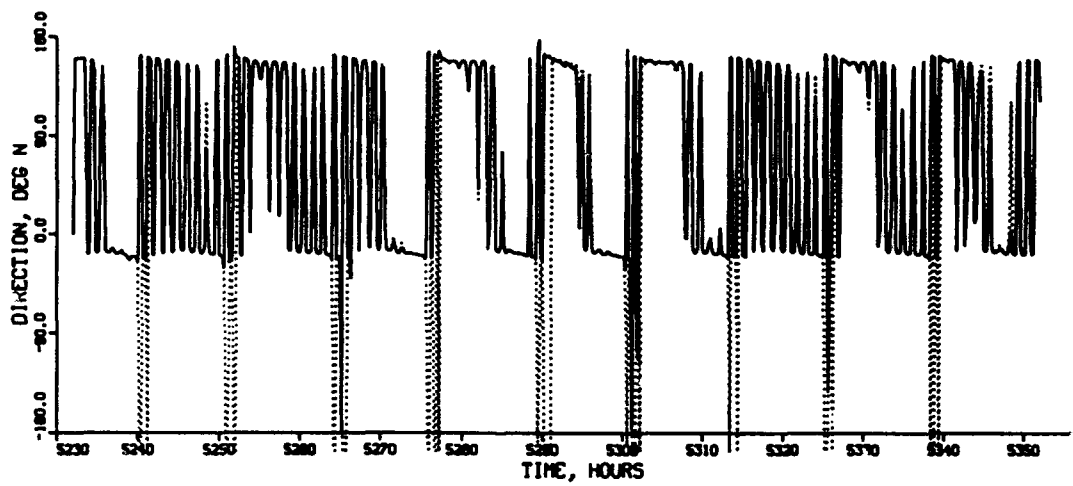
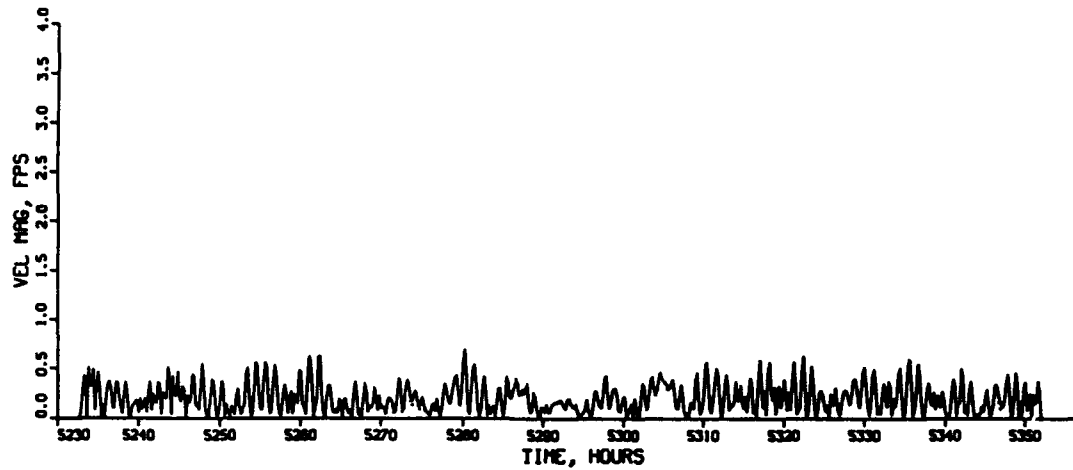


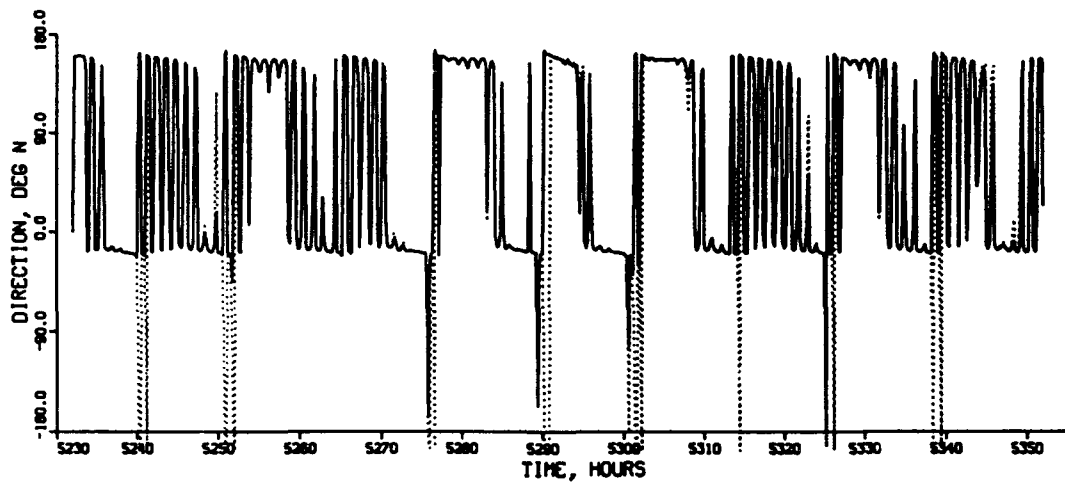
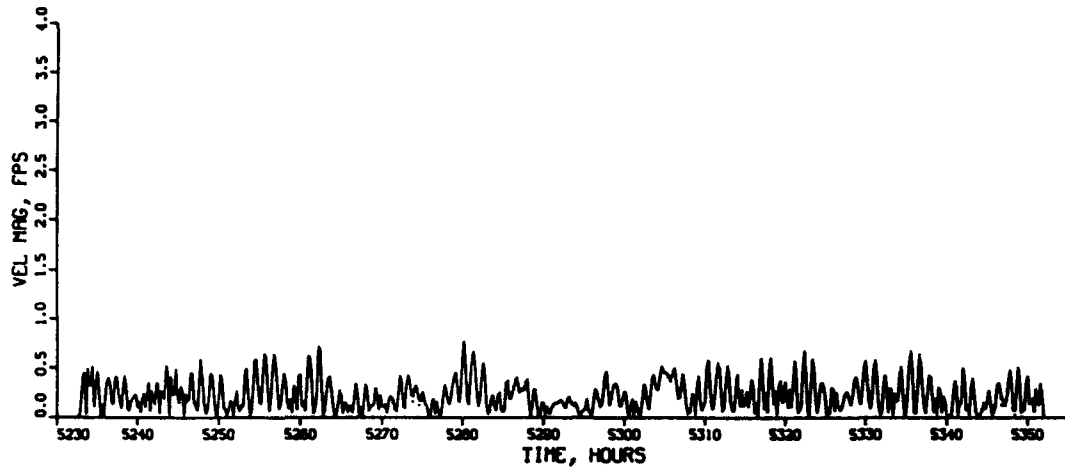
PLATE 35

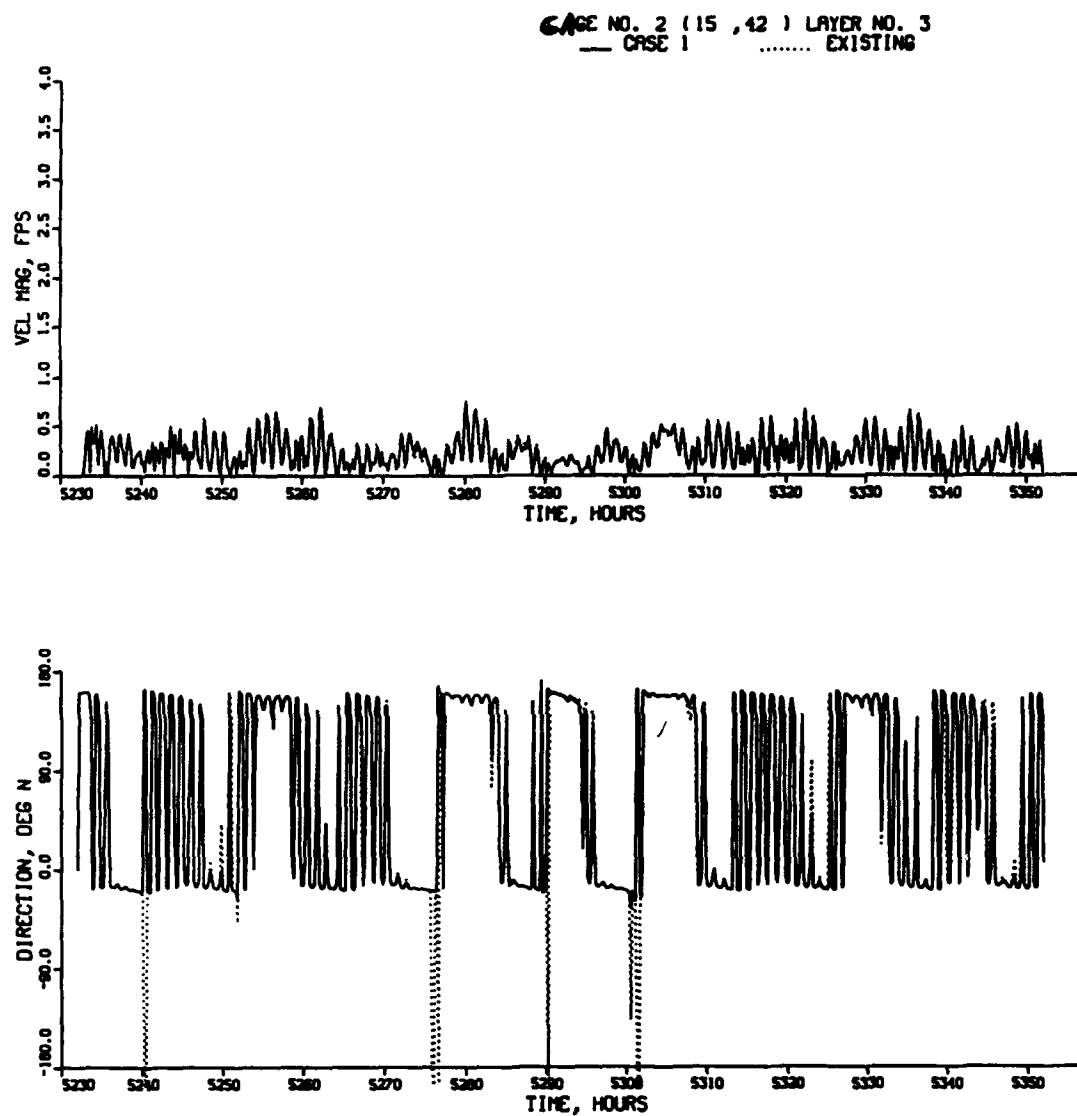


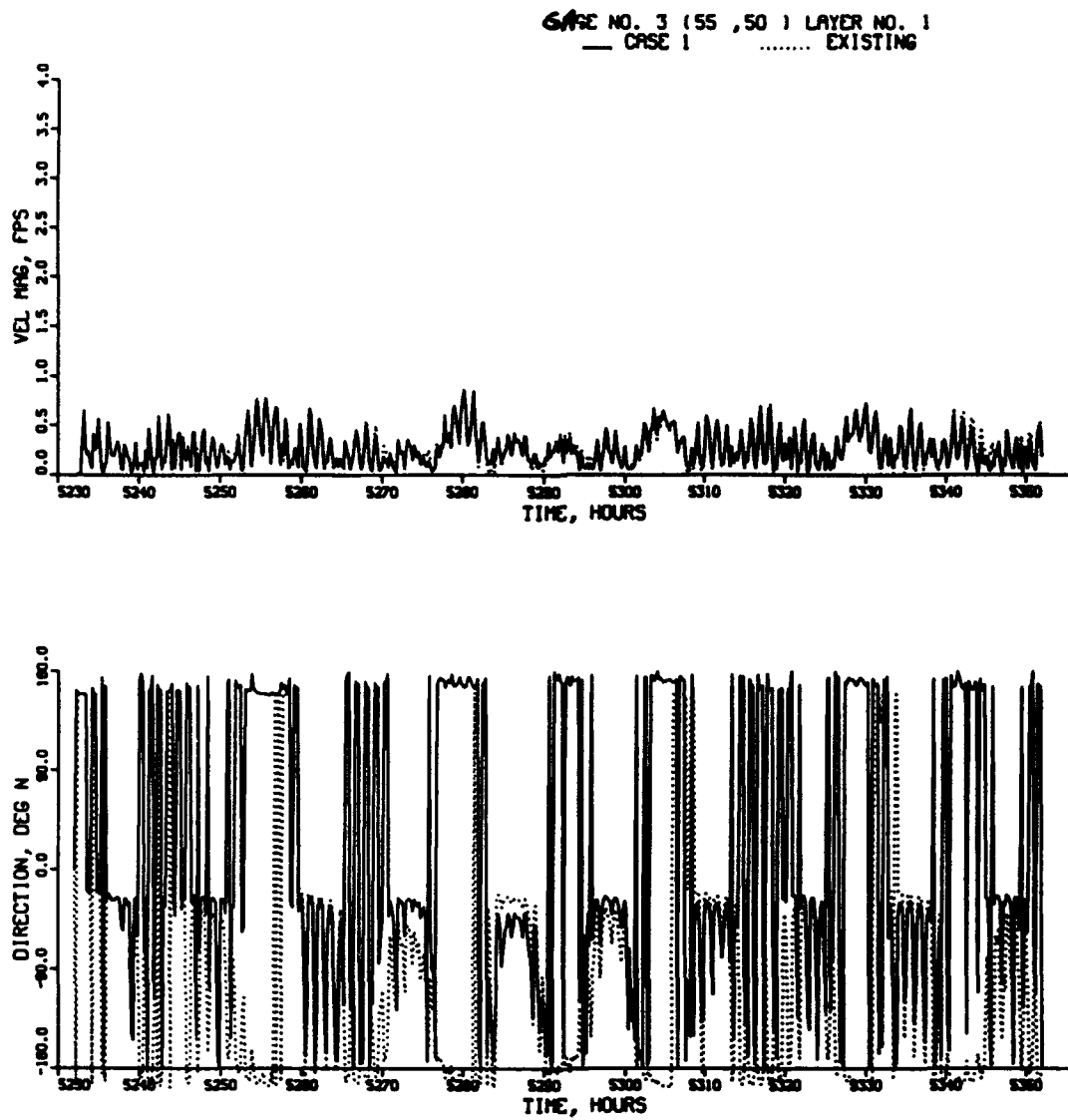
CASE NO. 2 (15, 42) LAYER NO. 1
— CASE 1 EXISTING



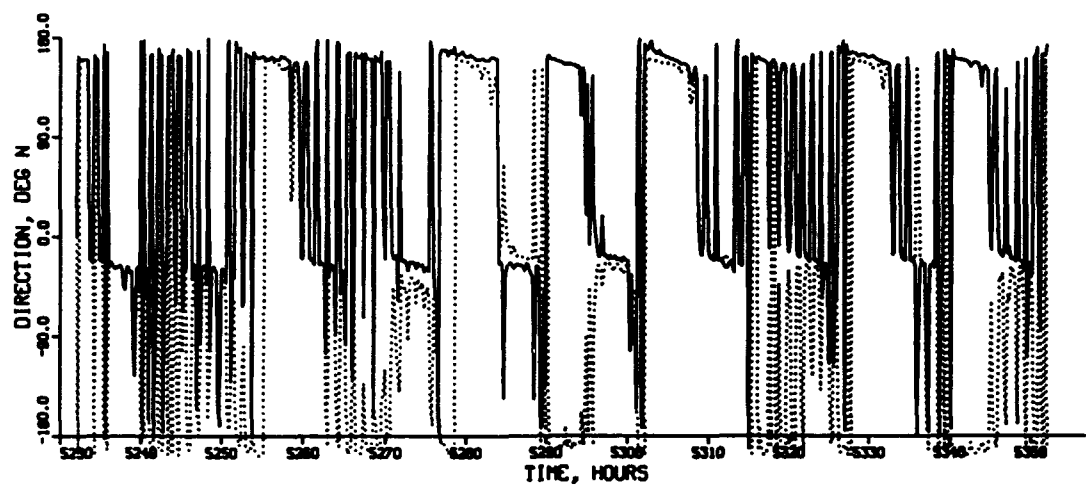
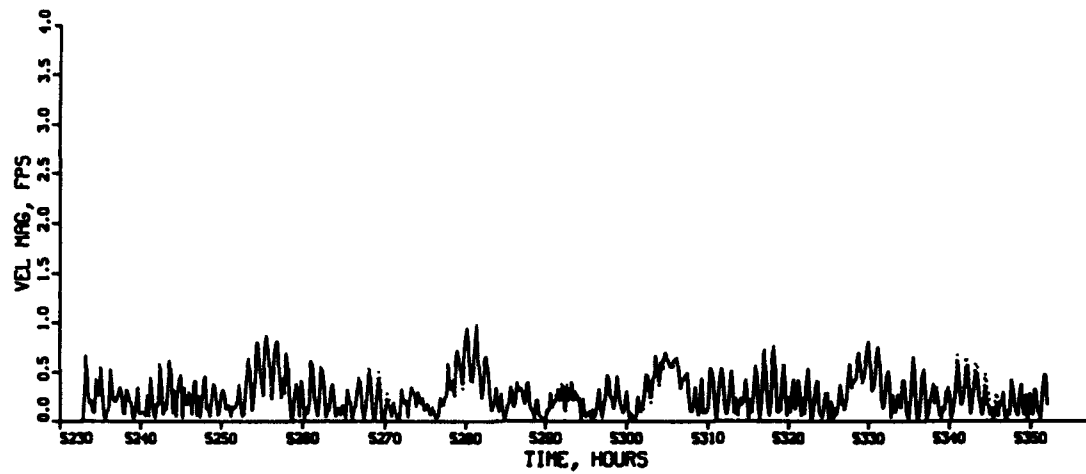
CASE NO. 2 (15, 42) LAYER NO. 2
— CASE 1 EXISTING

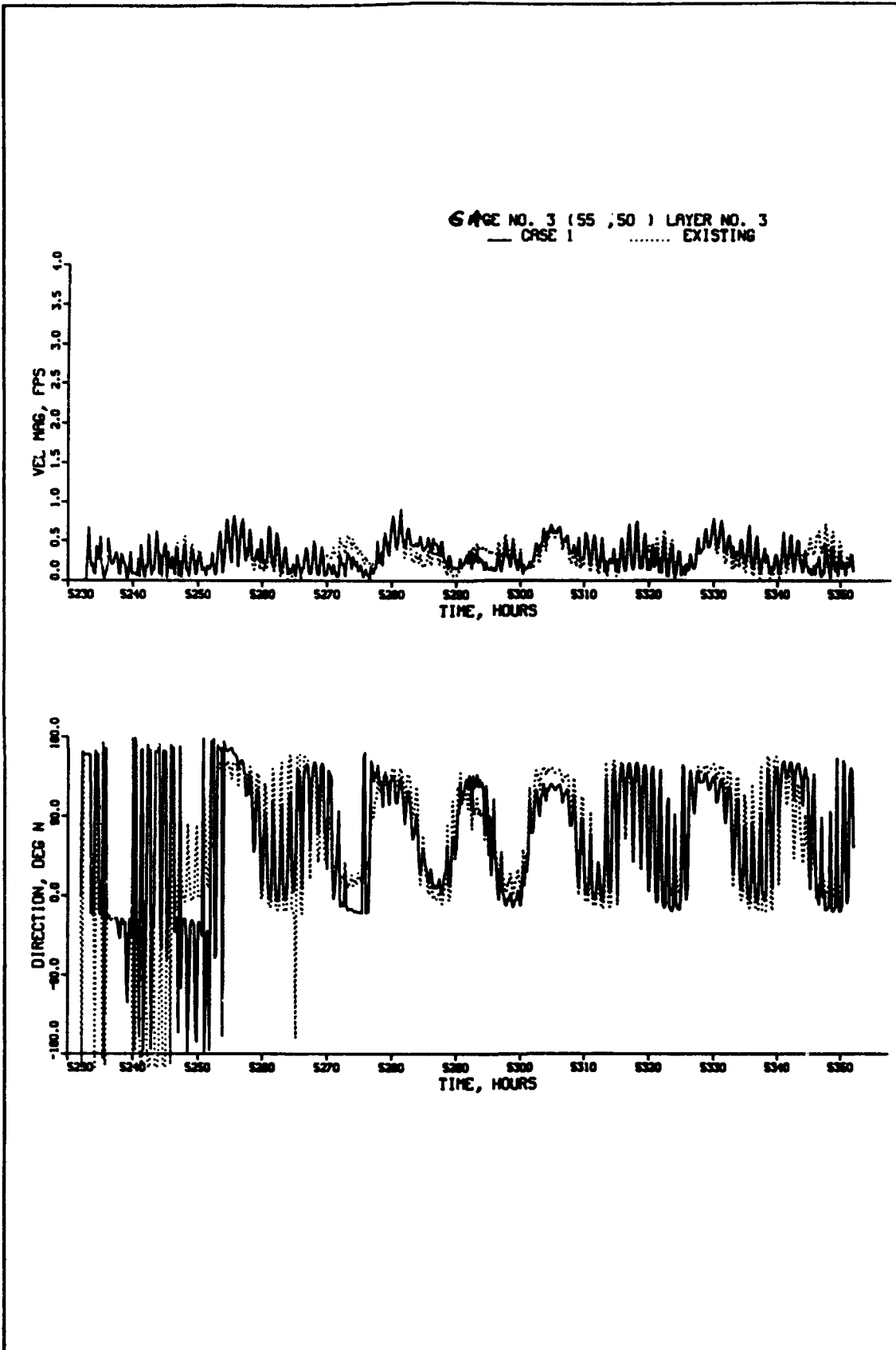




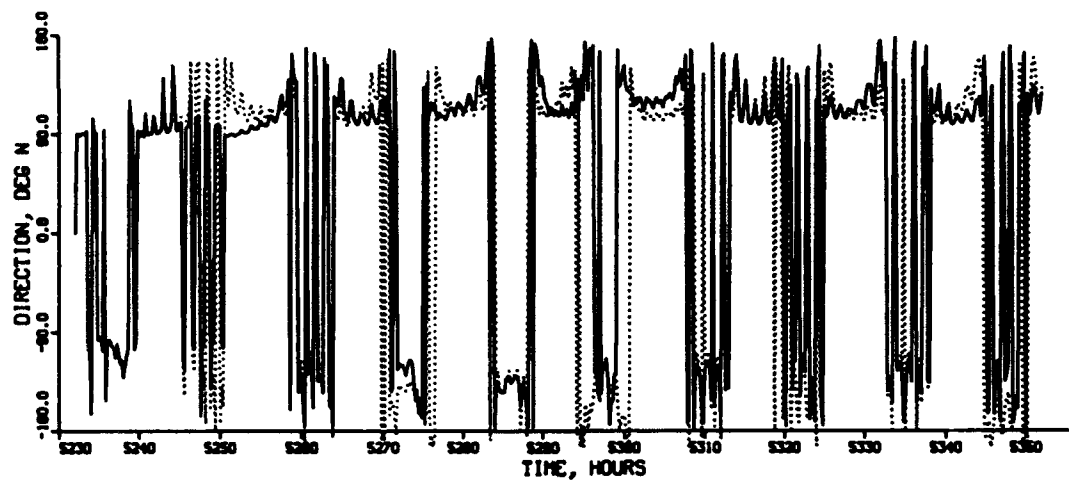
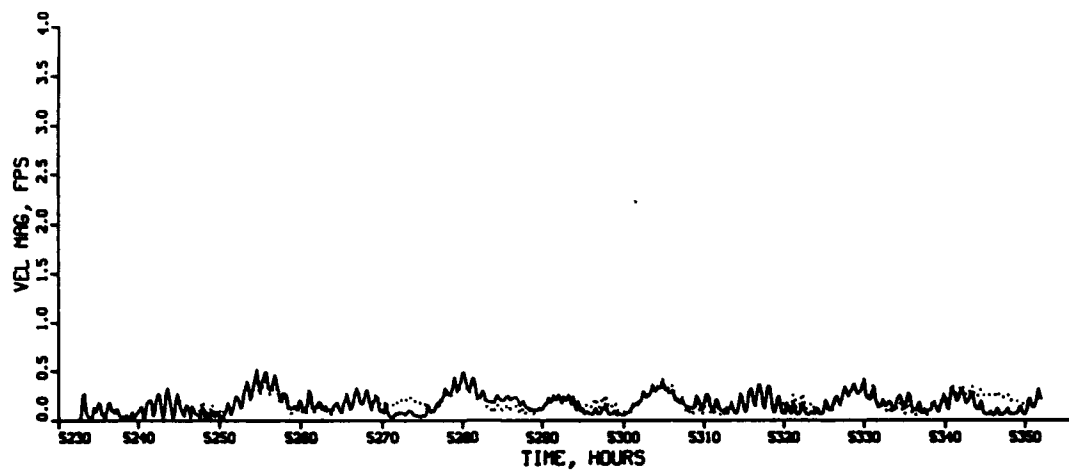


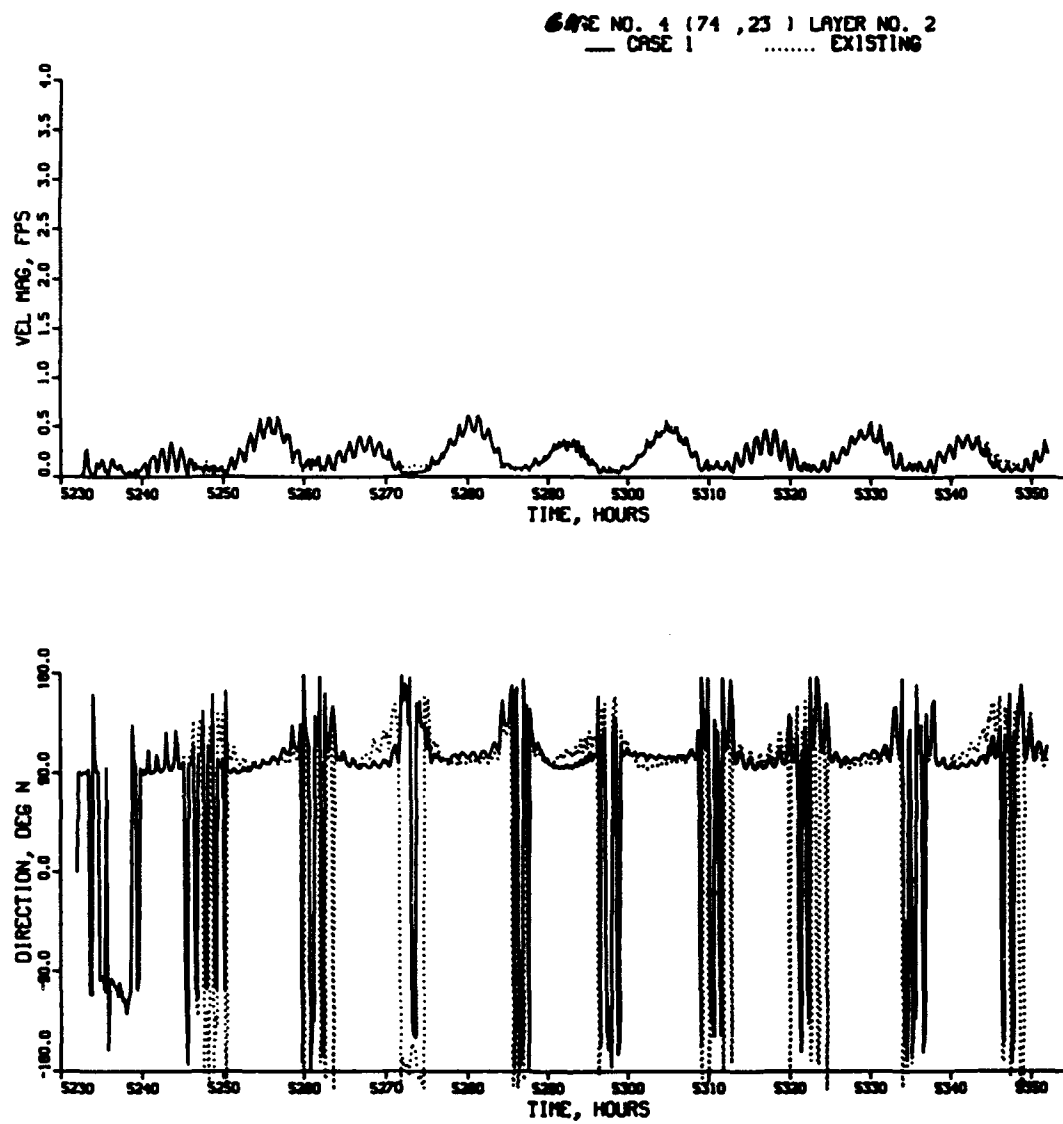
AGE NO. 3 (55 ,50) LAYER NO. 2
— CASE 1 EXISTING

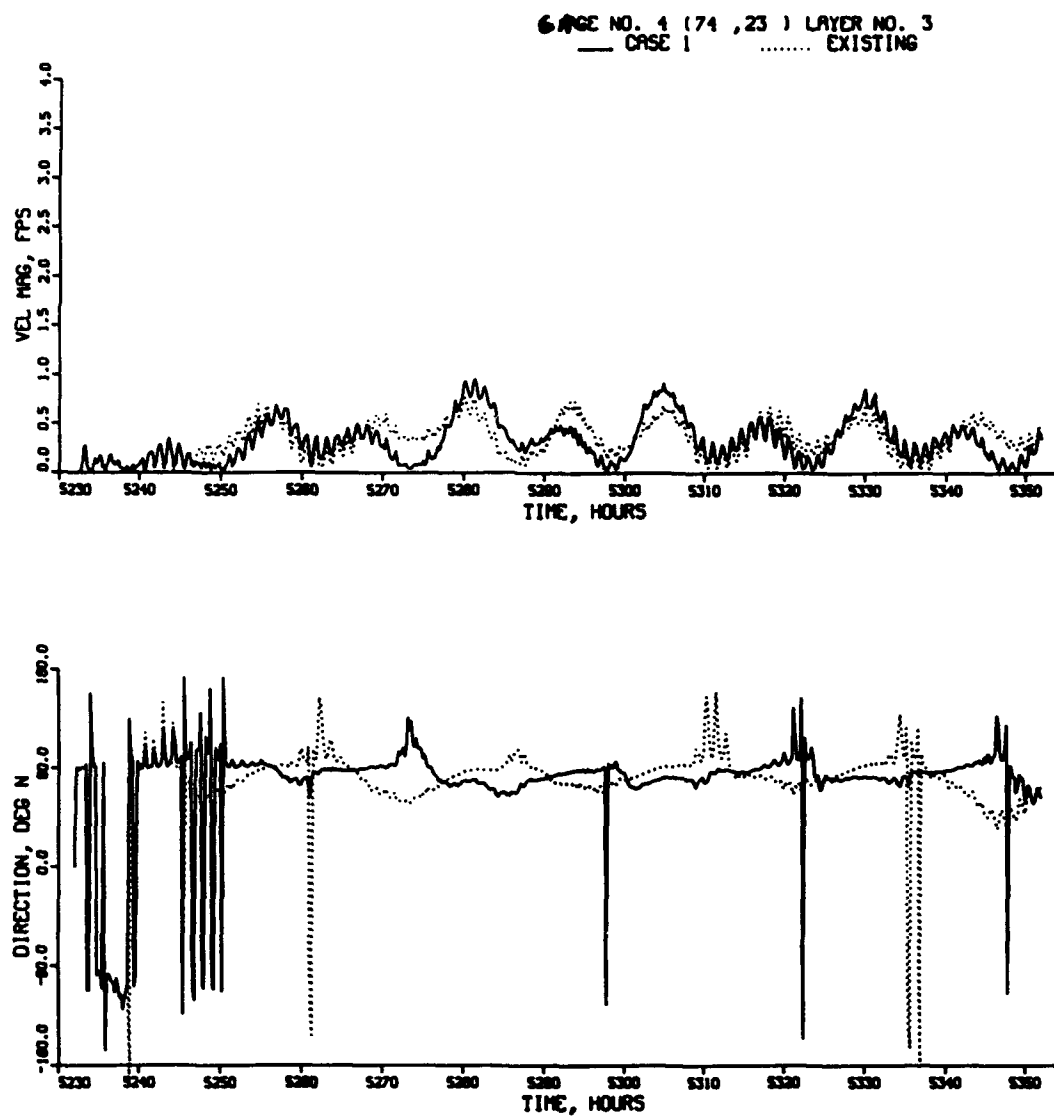




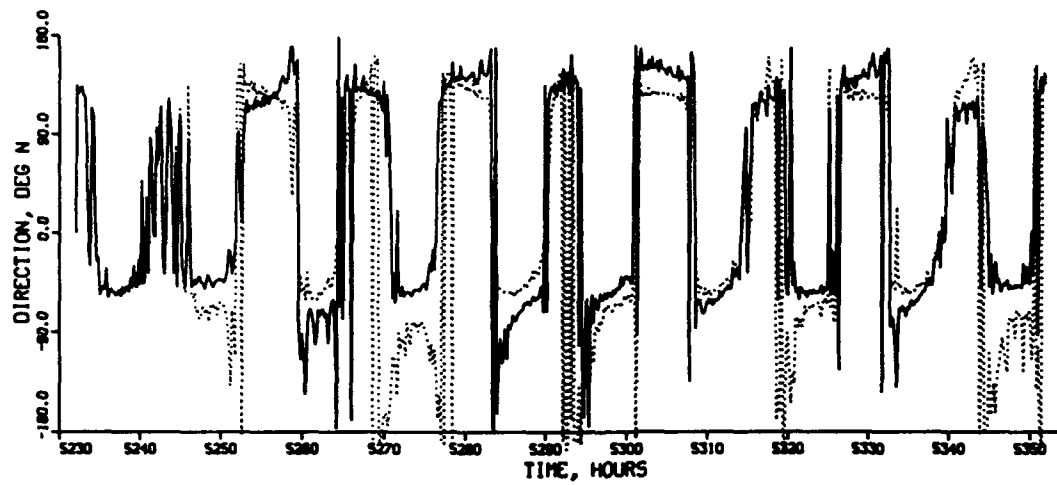
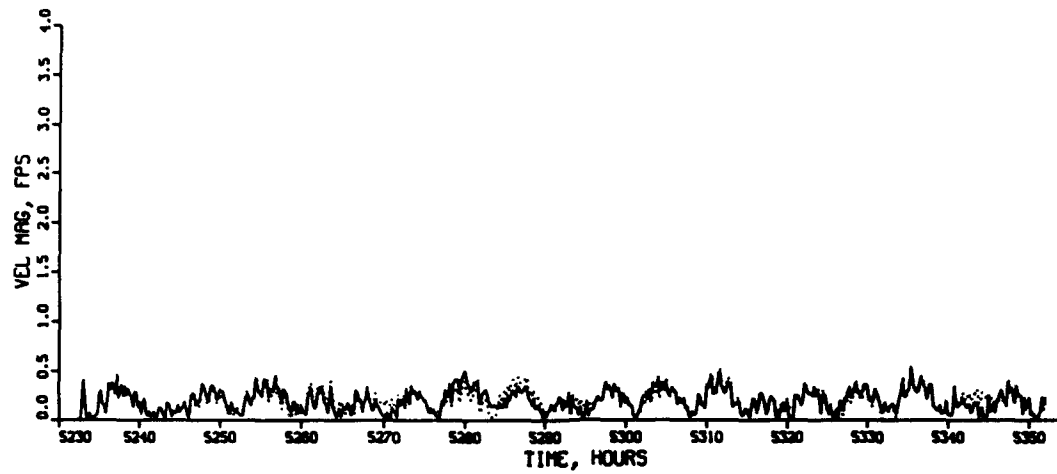
CASE NO. 4 (74, 23) LAYER NO. 1
— CASE 1 EXISTING

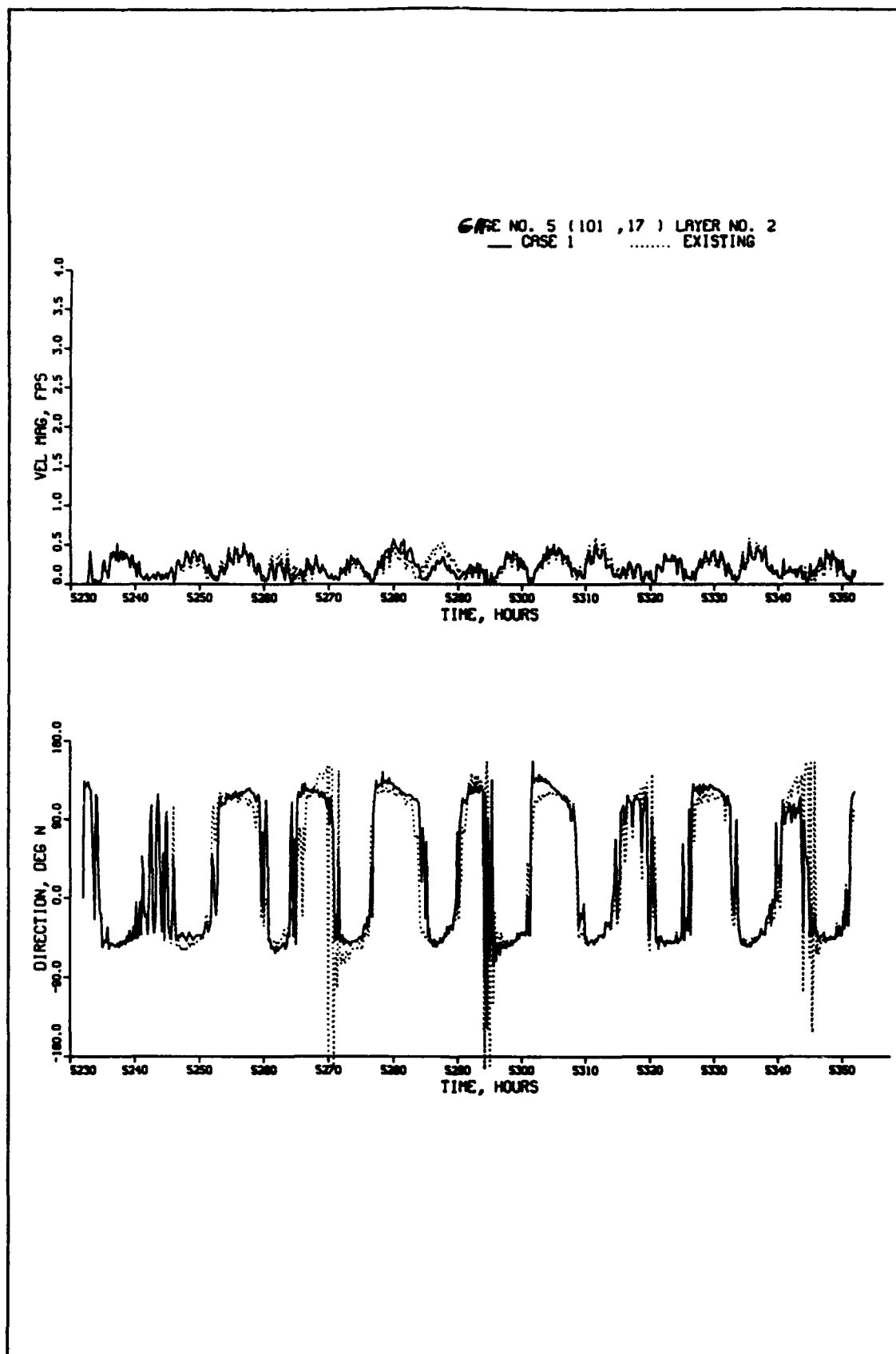




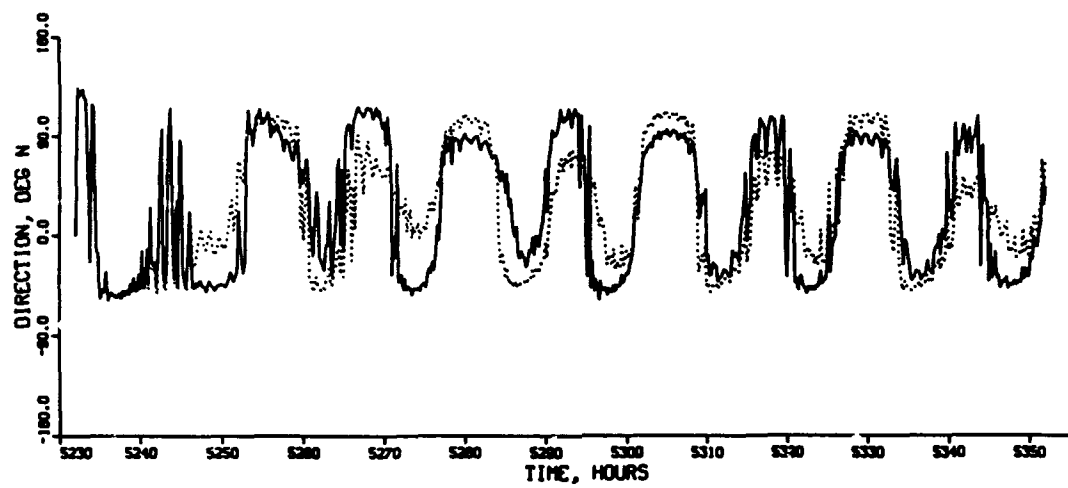
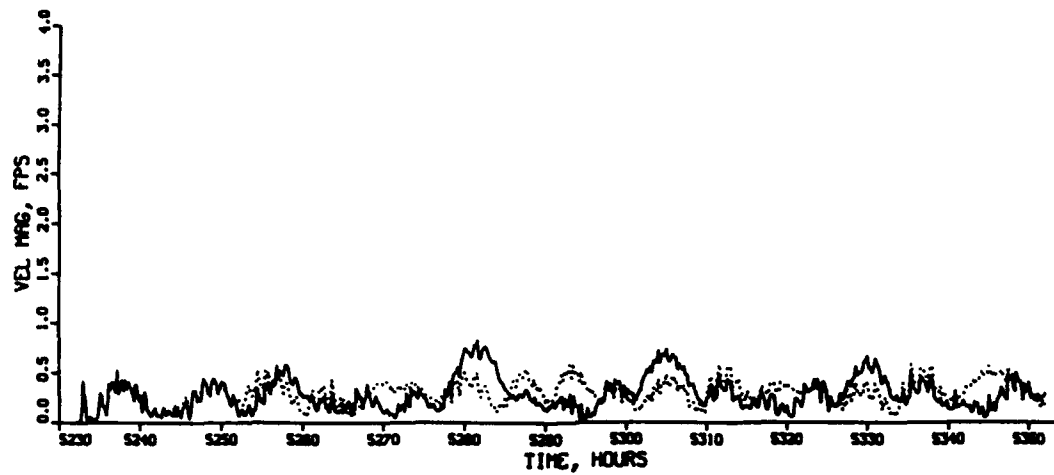


CAGE NO. 5 (101, 17) LAYER NO. 1
— CASE 1 EXISTING

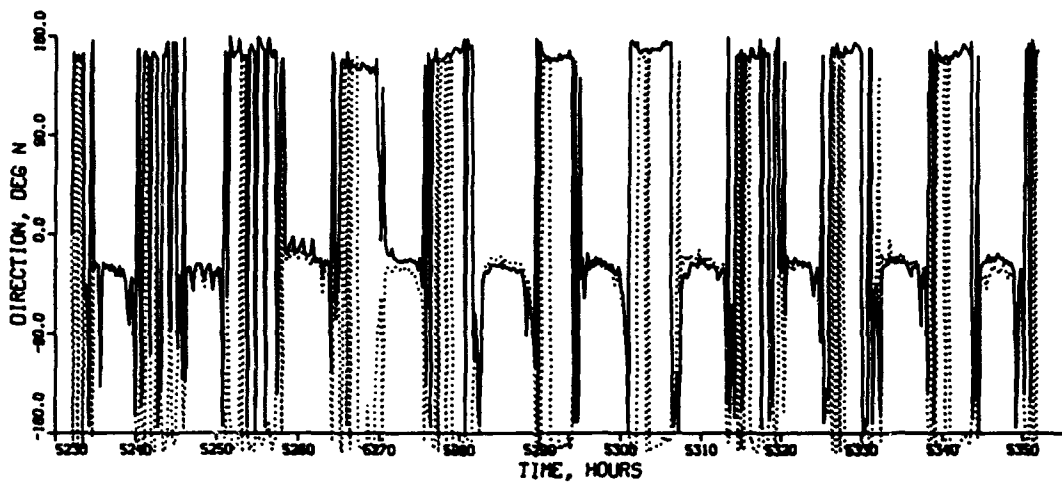
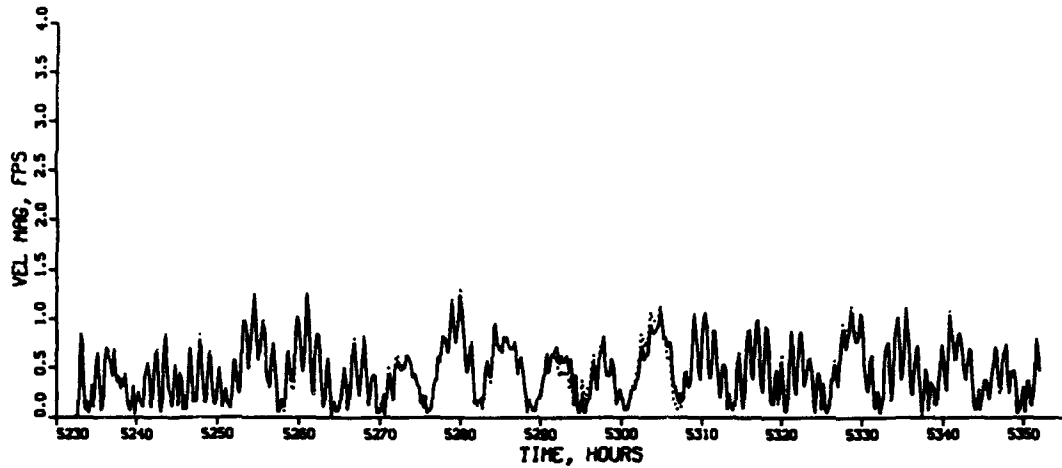


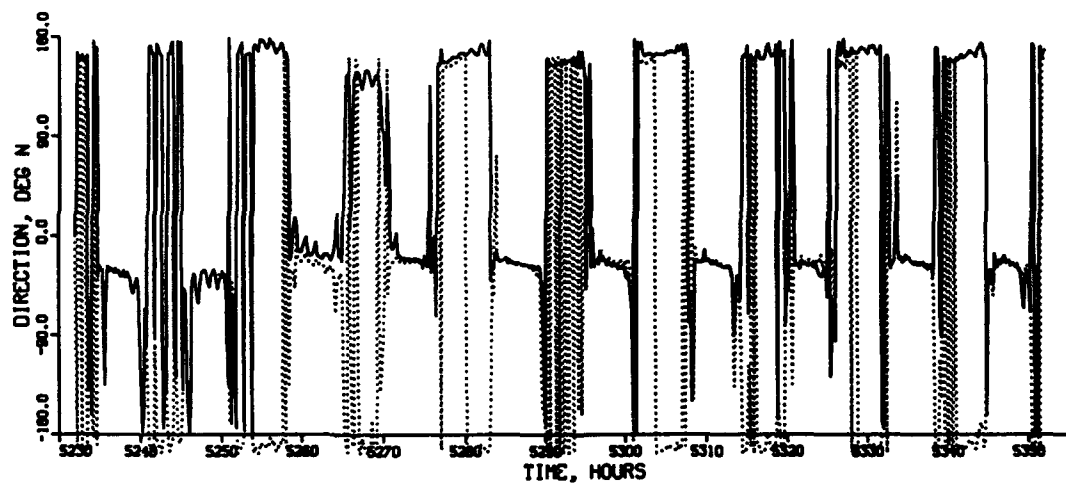
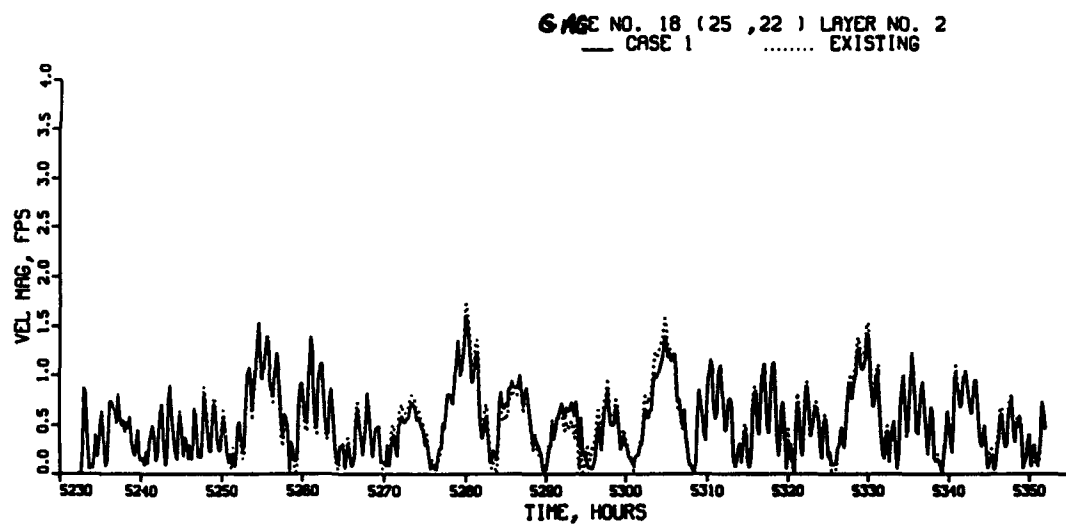


CASE NO. 5 (101, 17) LAYER NO. 3
— CASE 1 EXISTING

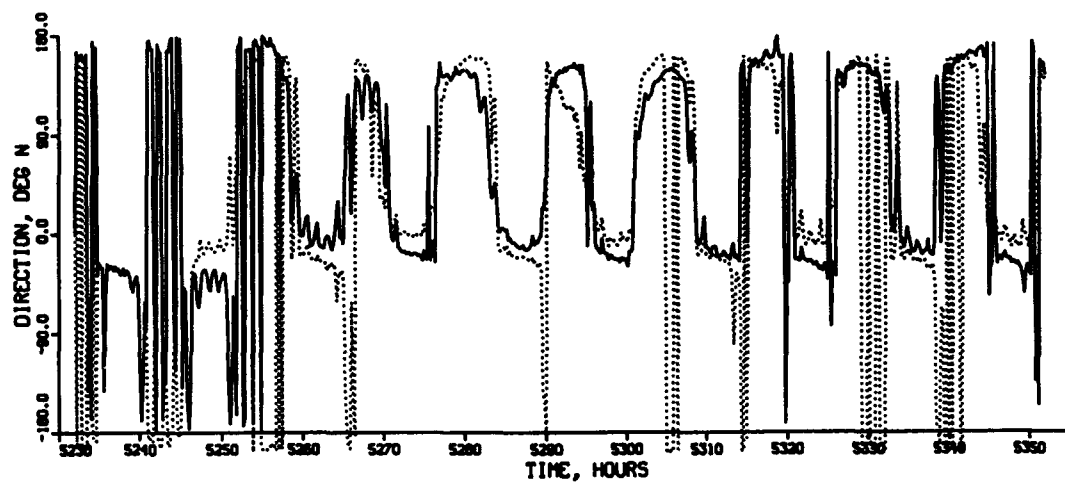
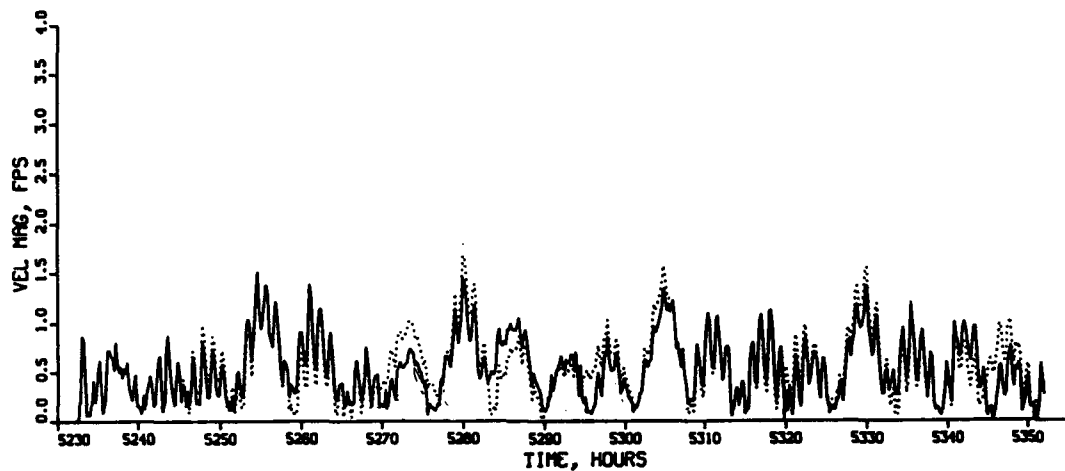


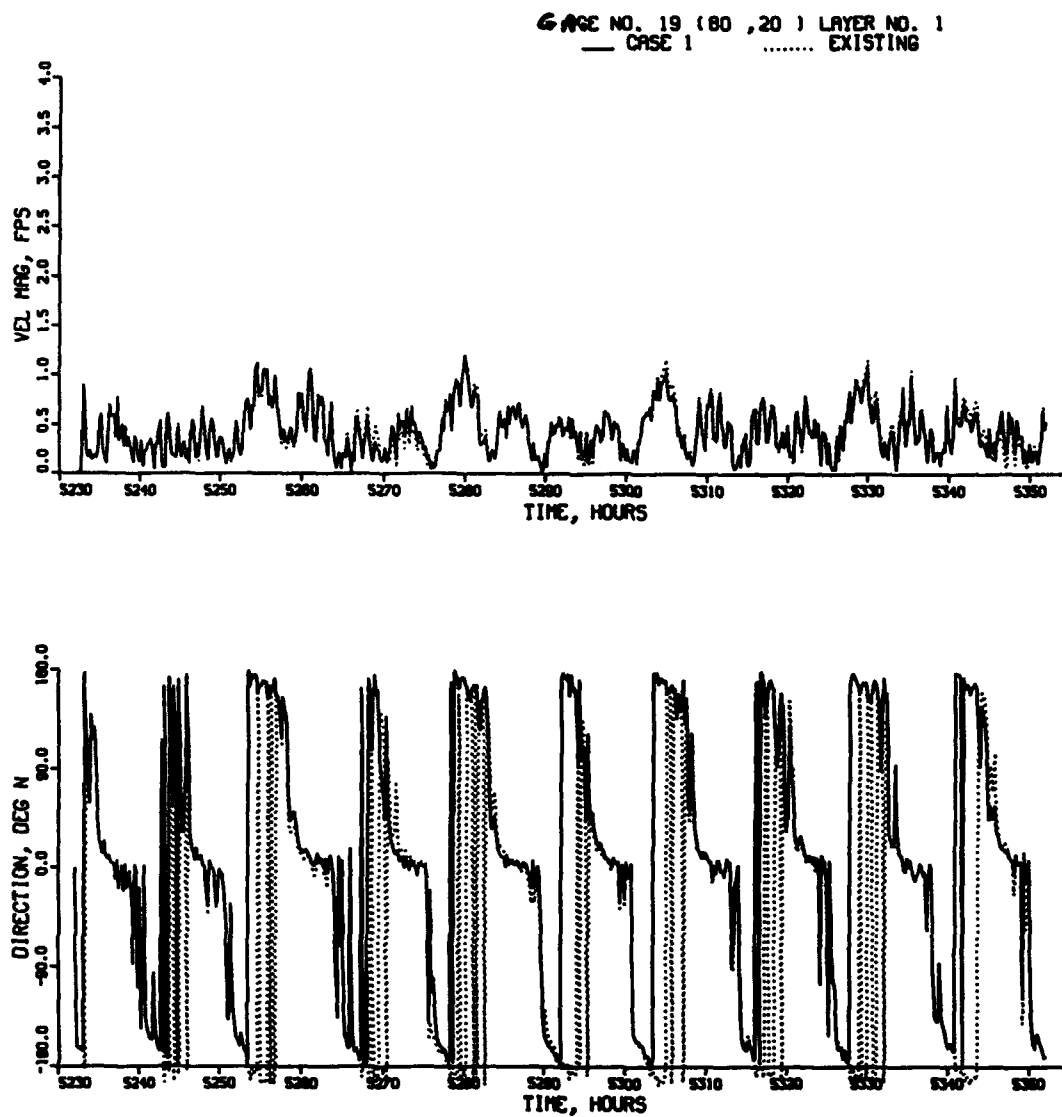
CASE NO. 18 (25, 22) LAYER NO. 1
— CASE 1 EXISTING



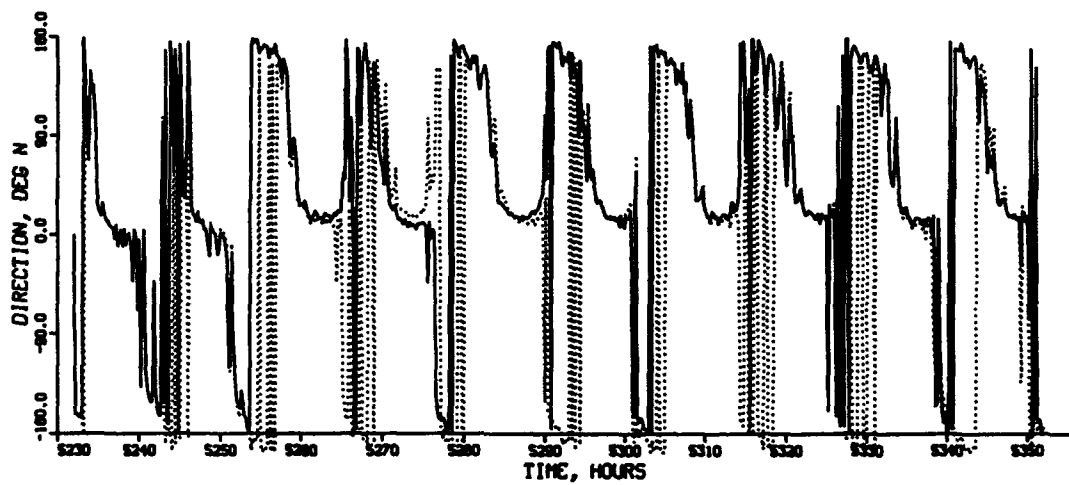
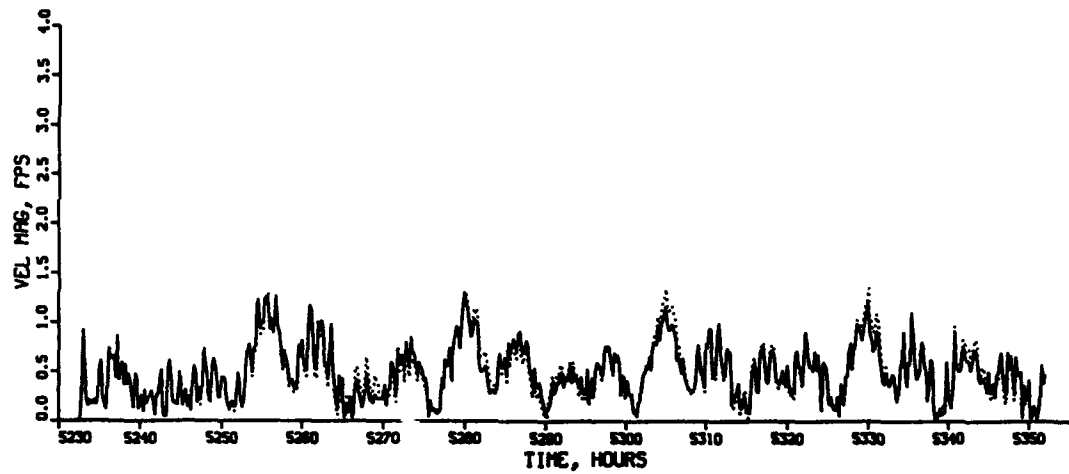


GARE NO. 18 (25 , 22) LAYER NO. 3
— CASE 1 EXISTING

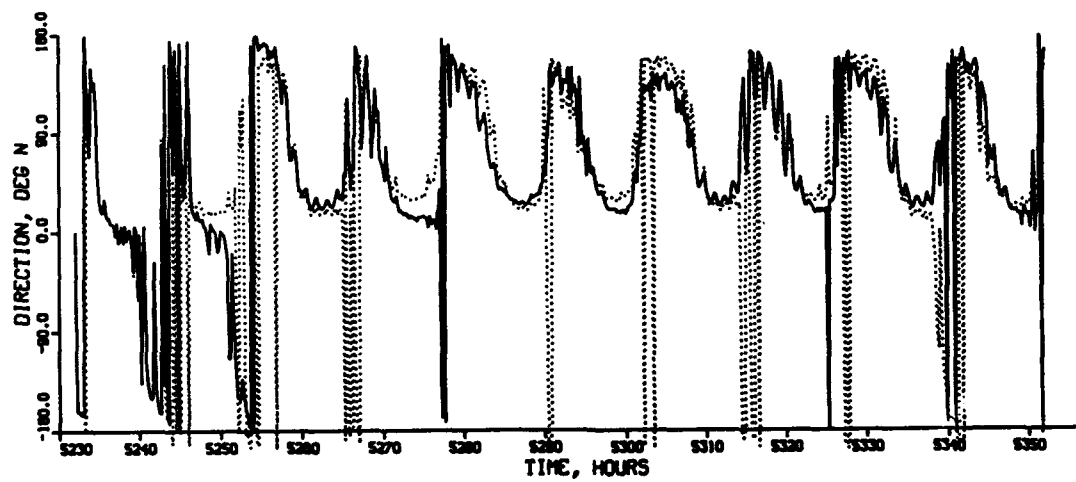
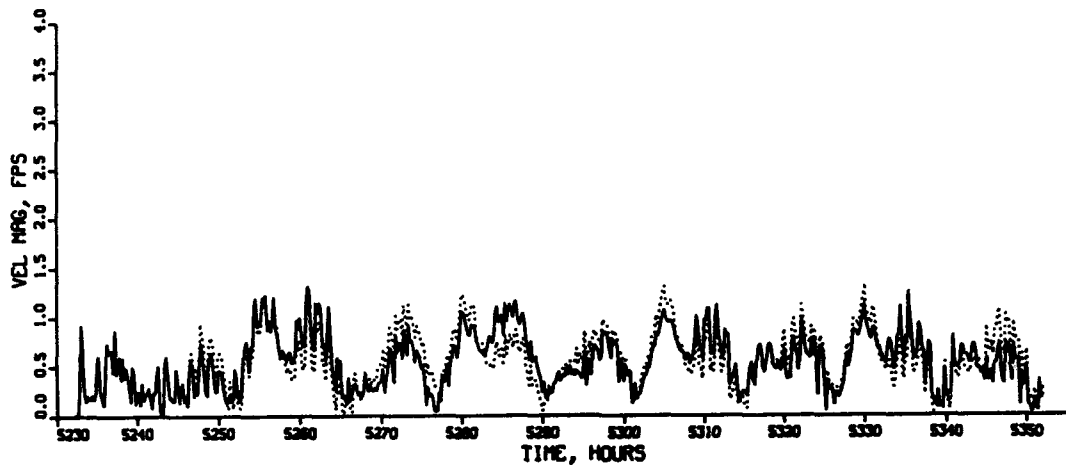




GAGE NO. 19 (80 , 20) LAYER NO. 2
— CASE 1 EXISTING

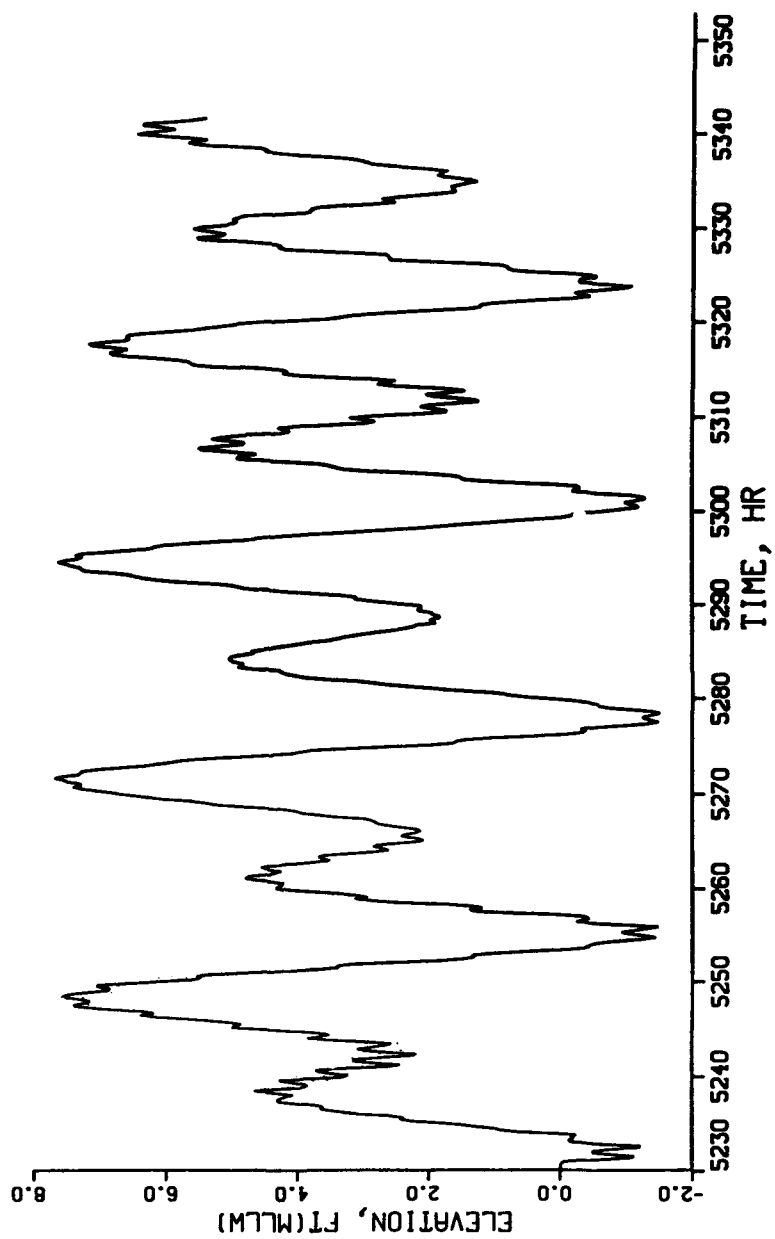


GAGE NO. 19 (80, 20) LAYER NO. 3
— CASE 1 EXISTING

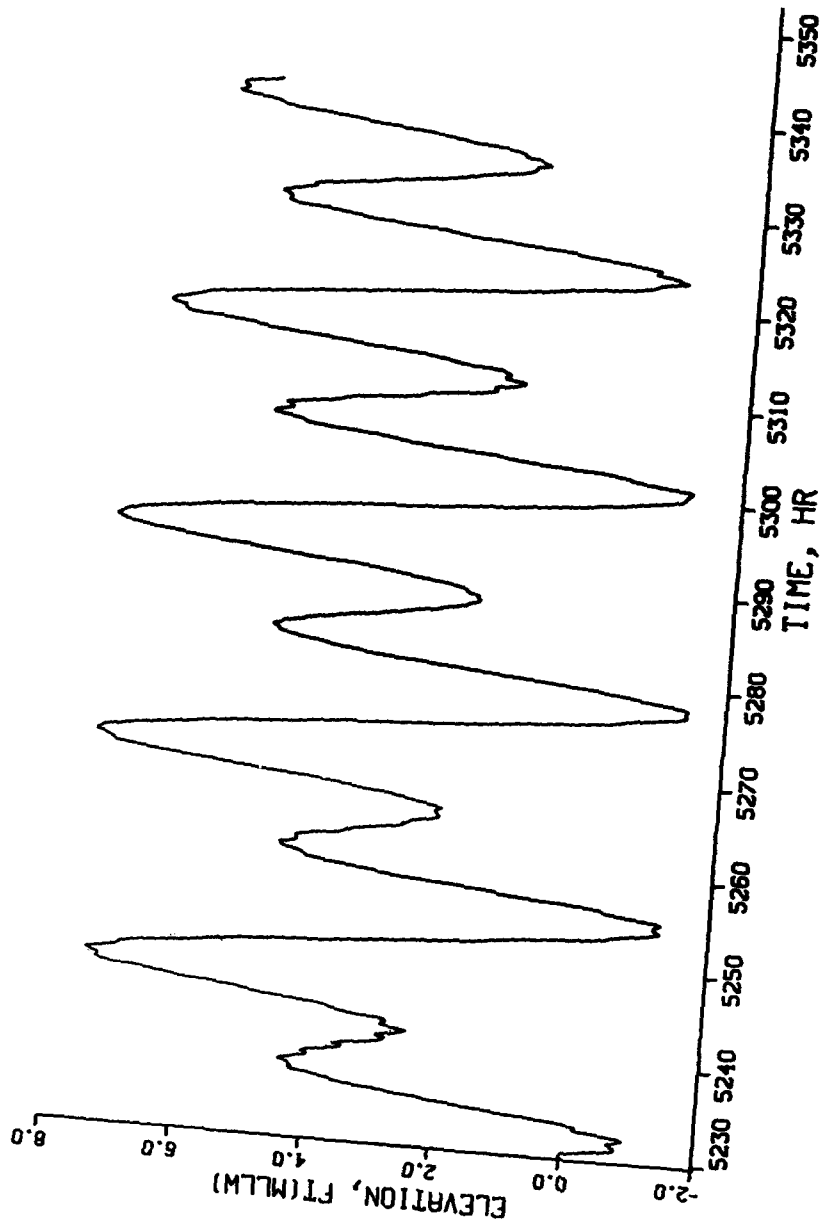


GAGE NO. 1 (46 , 80)

— CASE 1 EXISTING

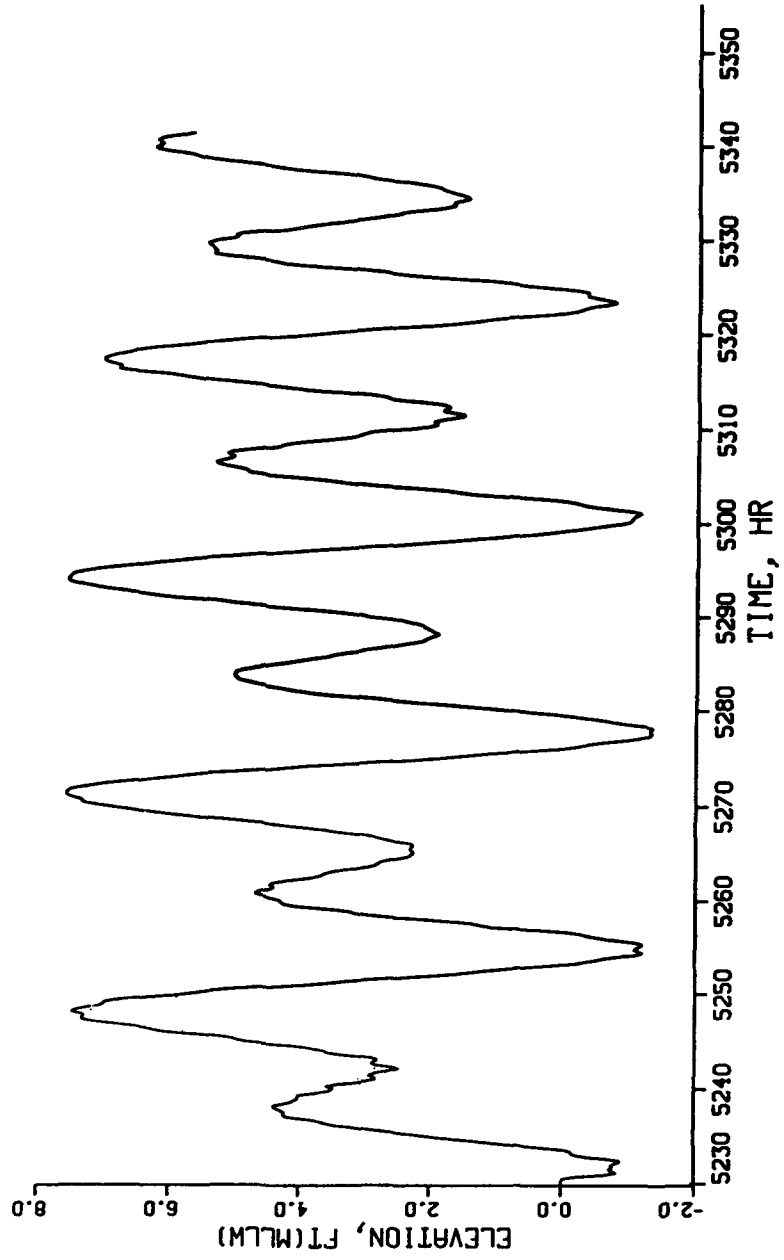


GAGE NO. 2 (15 , 42)
— CASE 1 EXISTING



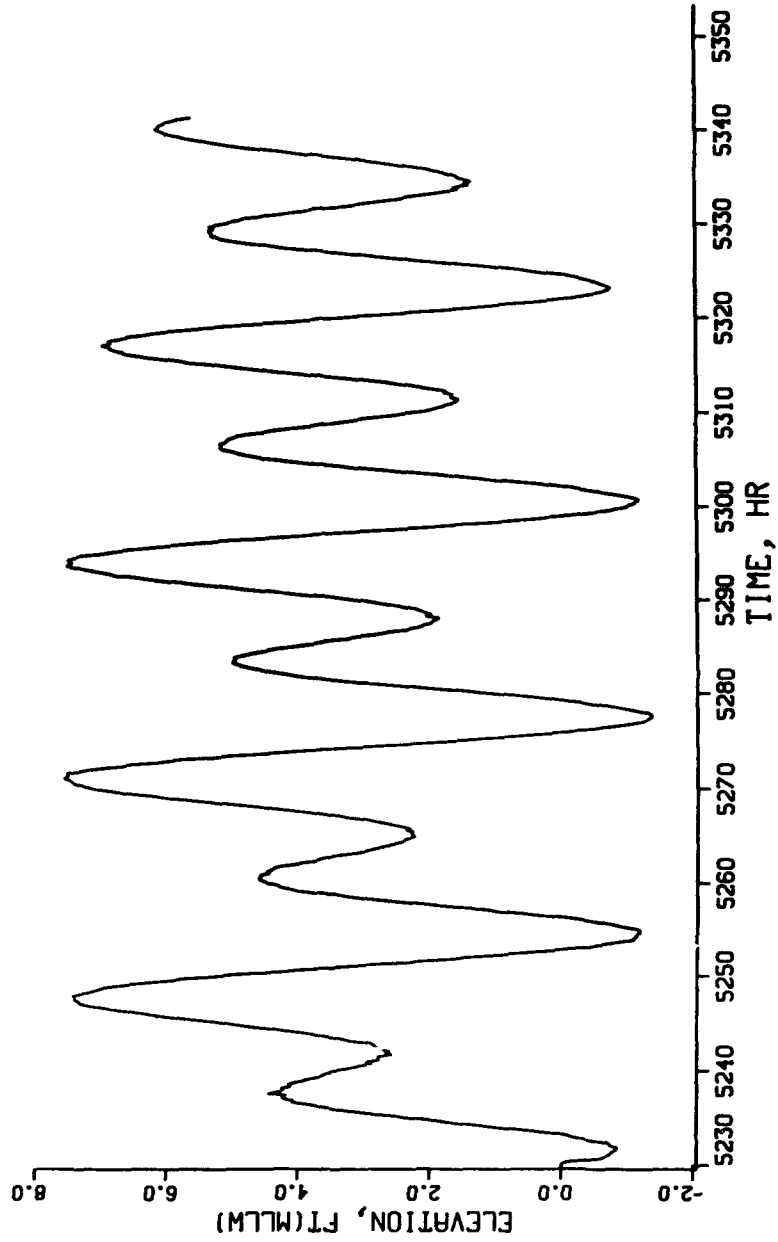
GAGE NO. 3 (55 , 50)

— CASE 1 EXISTING



GAGE NO. 5 (101 , 17)

— CASE 1 EXISTING



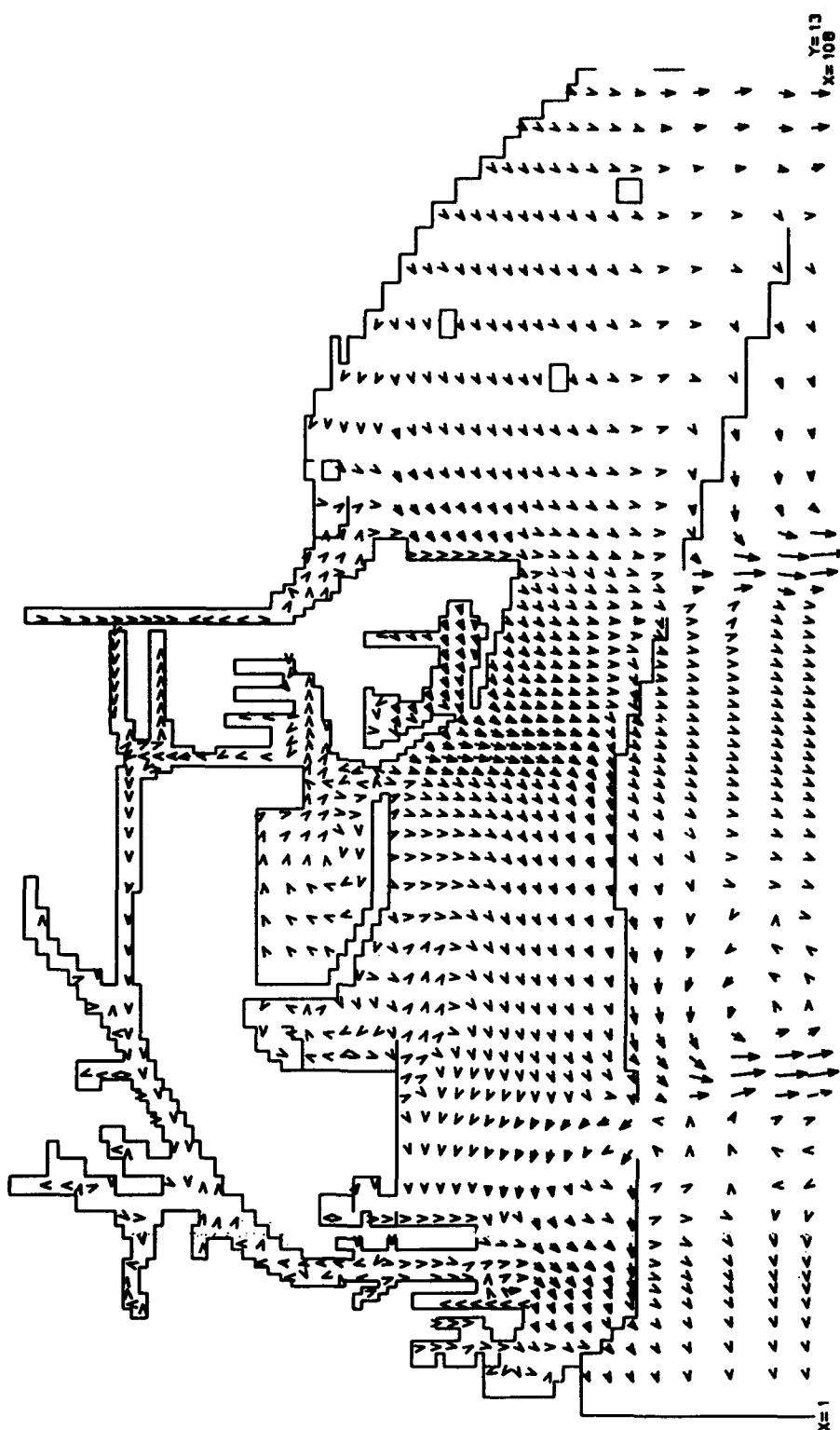
LA-LB HARBORS: CASE 1

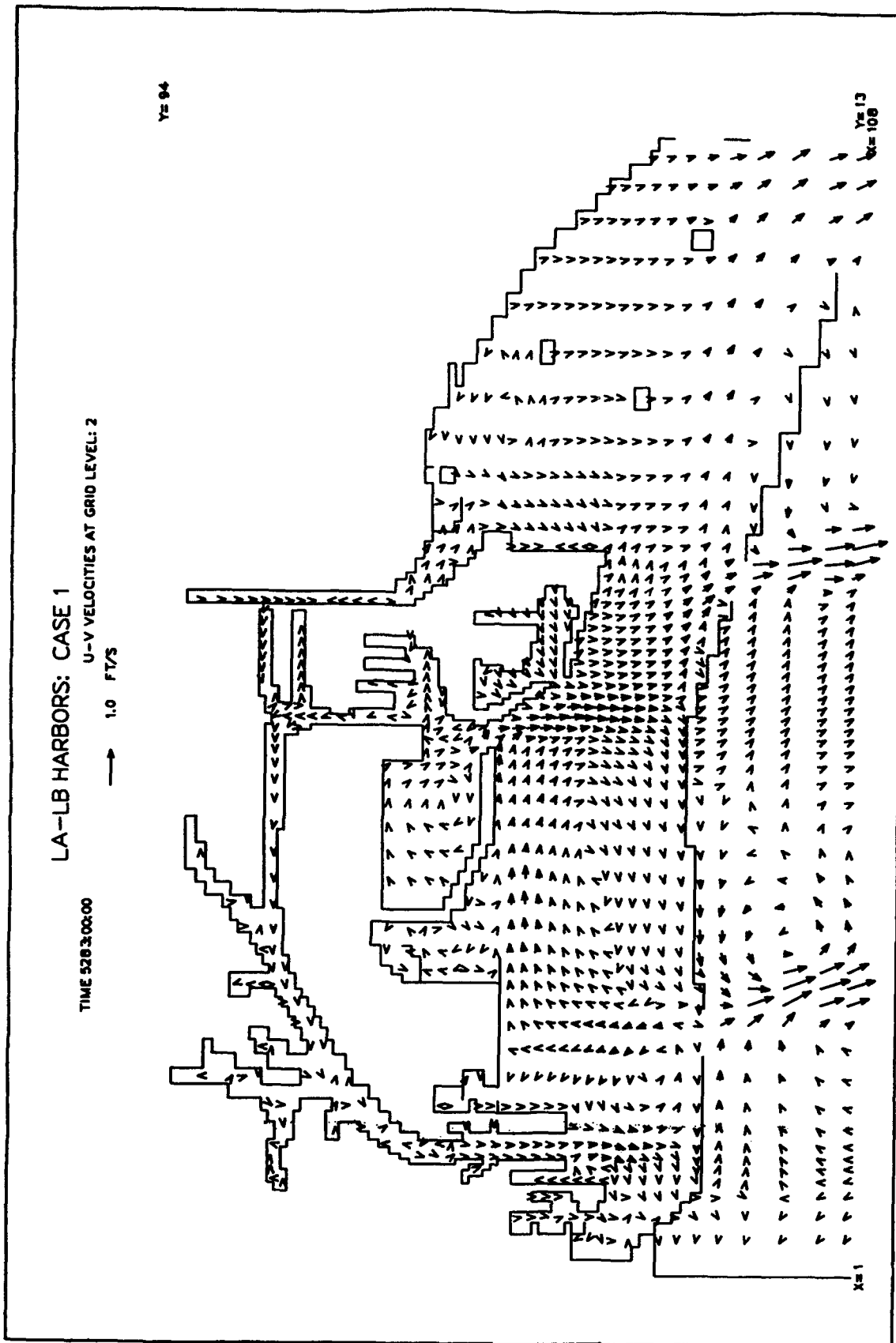
TIME 528 3:00:00

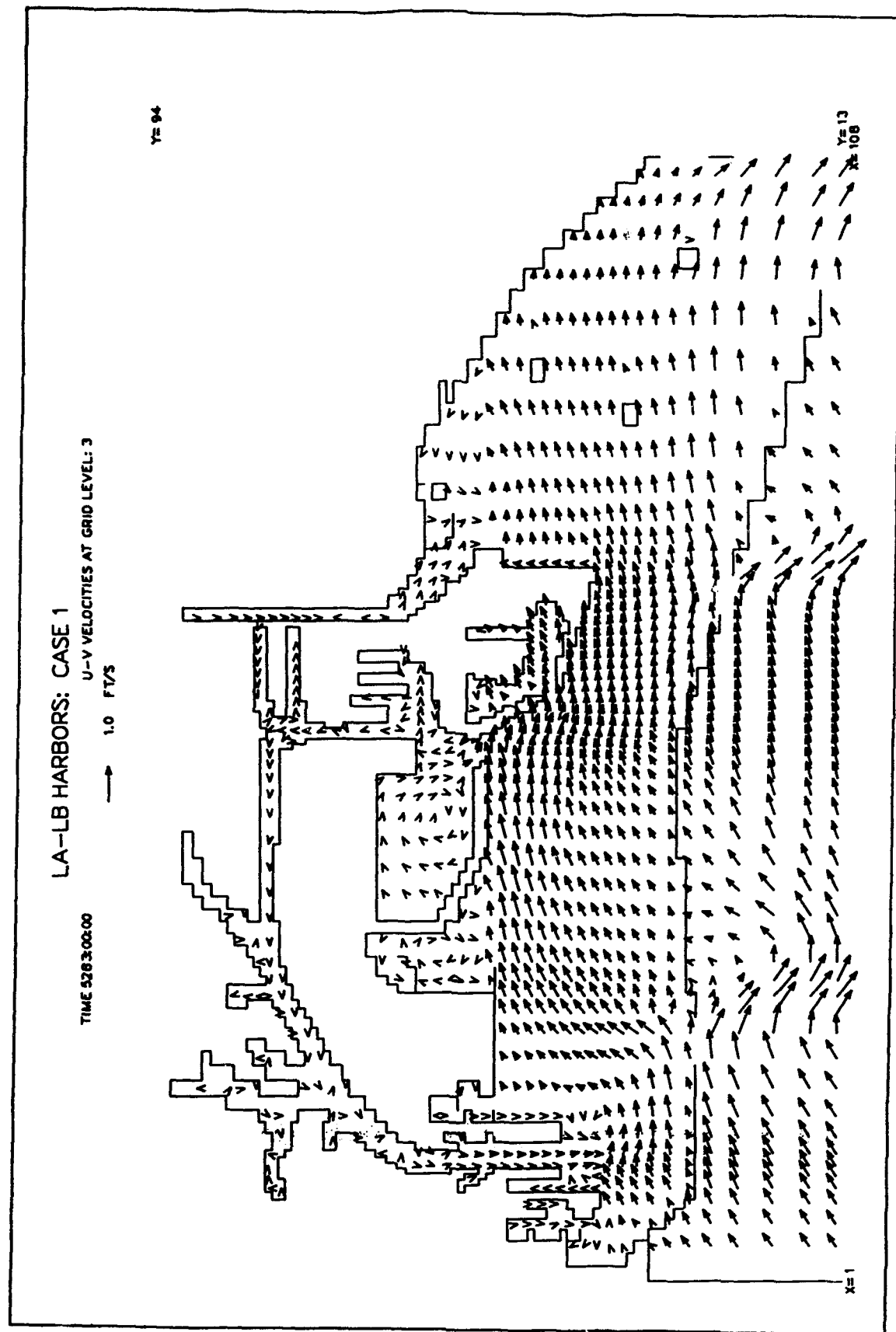
U-V VELOCITIES AT GRID LEVEL: 1

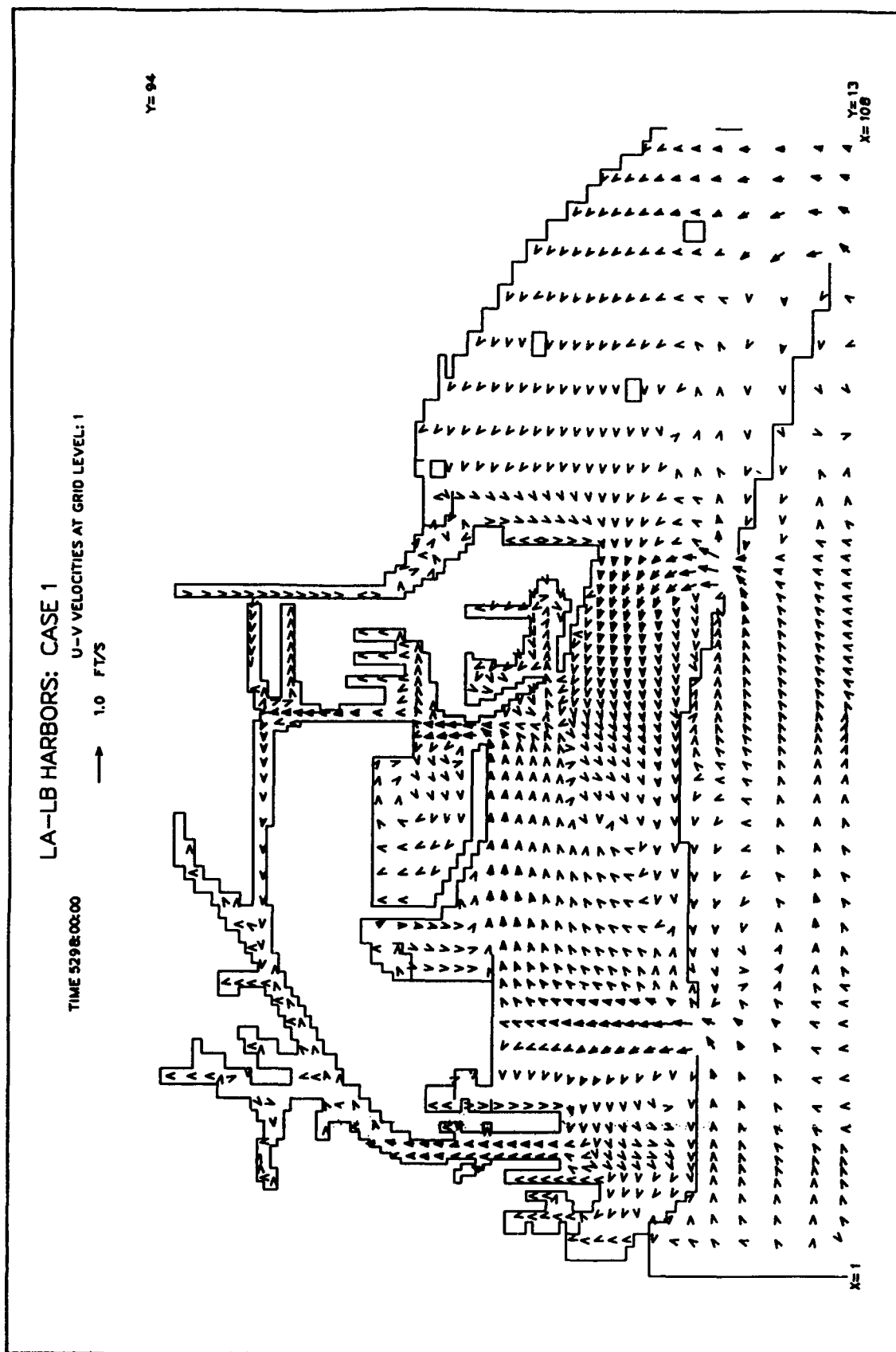
→ 1.0 FT/S

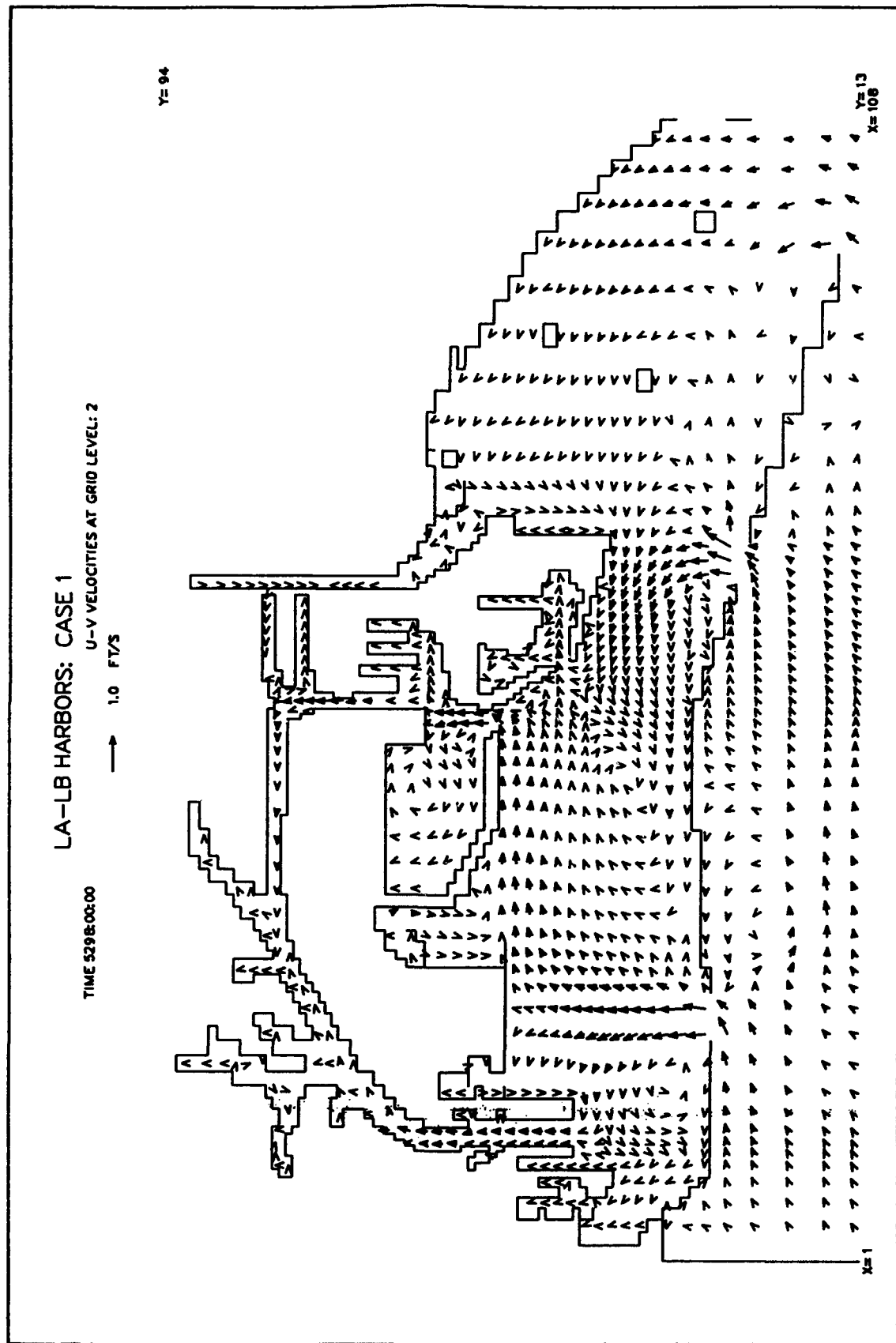
Y=94

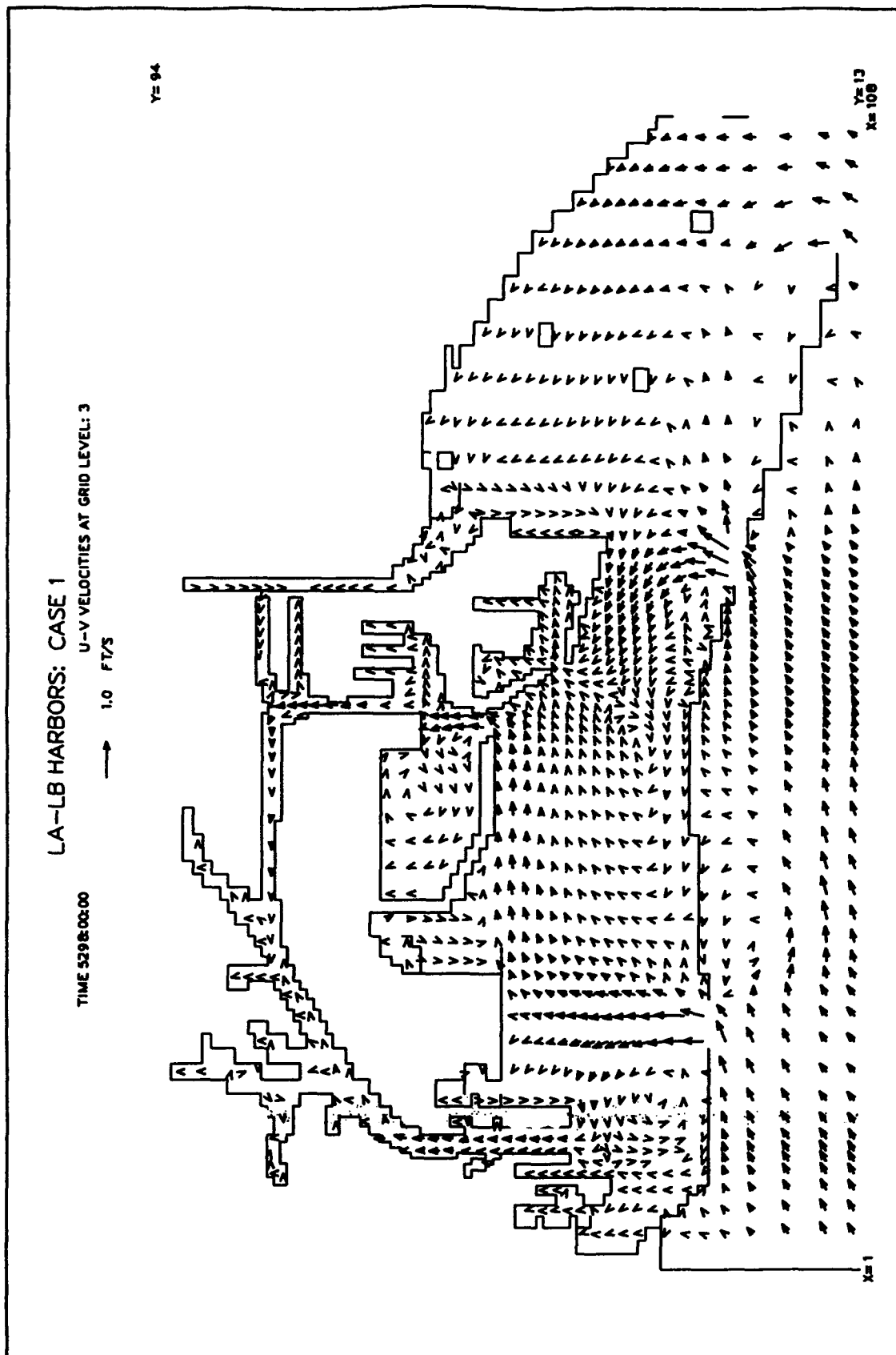


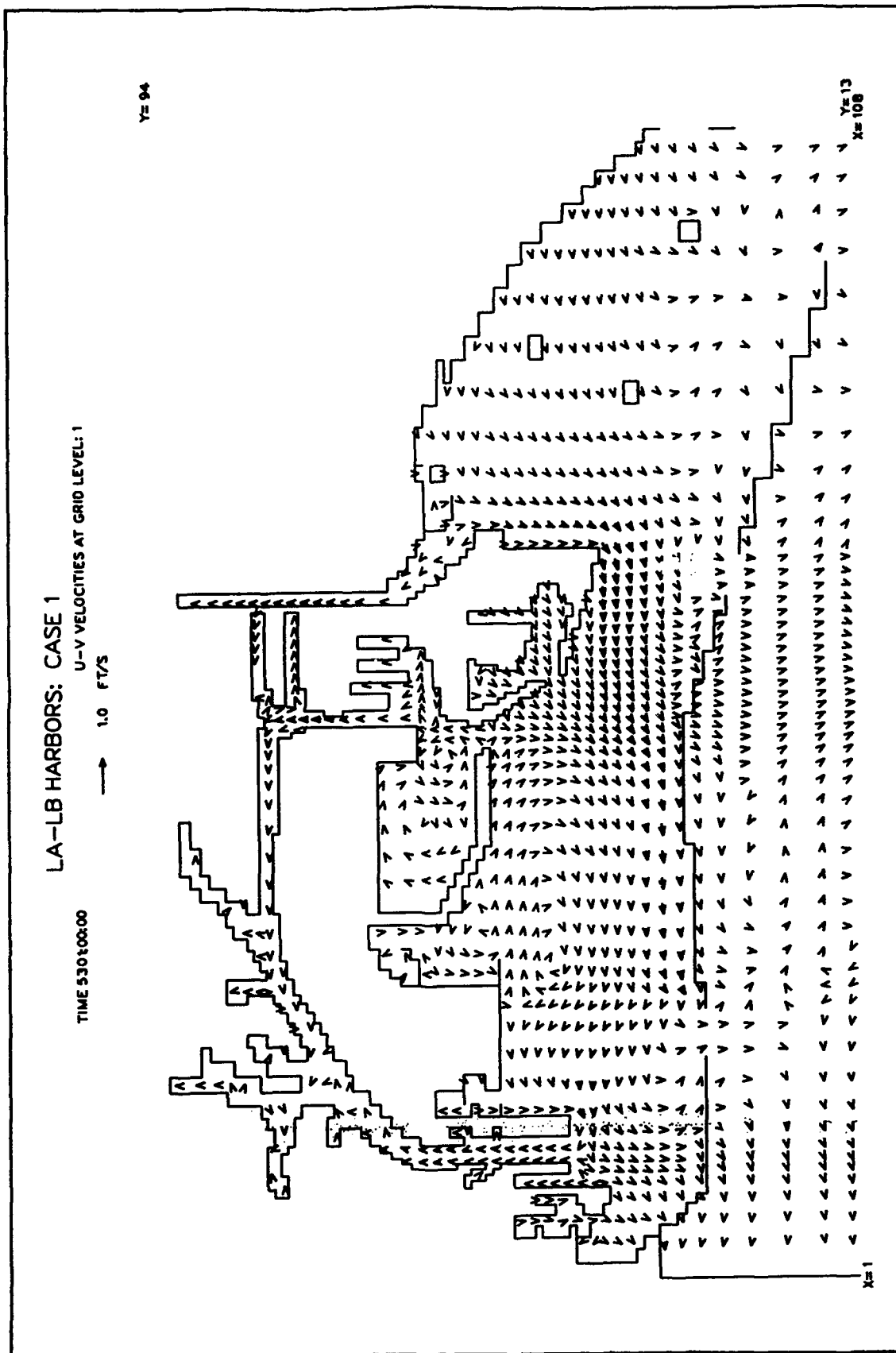


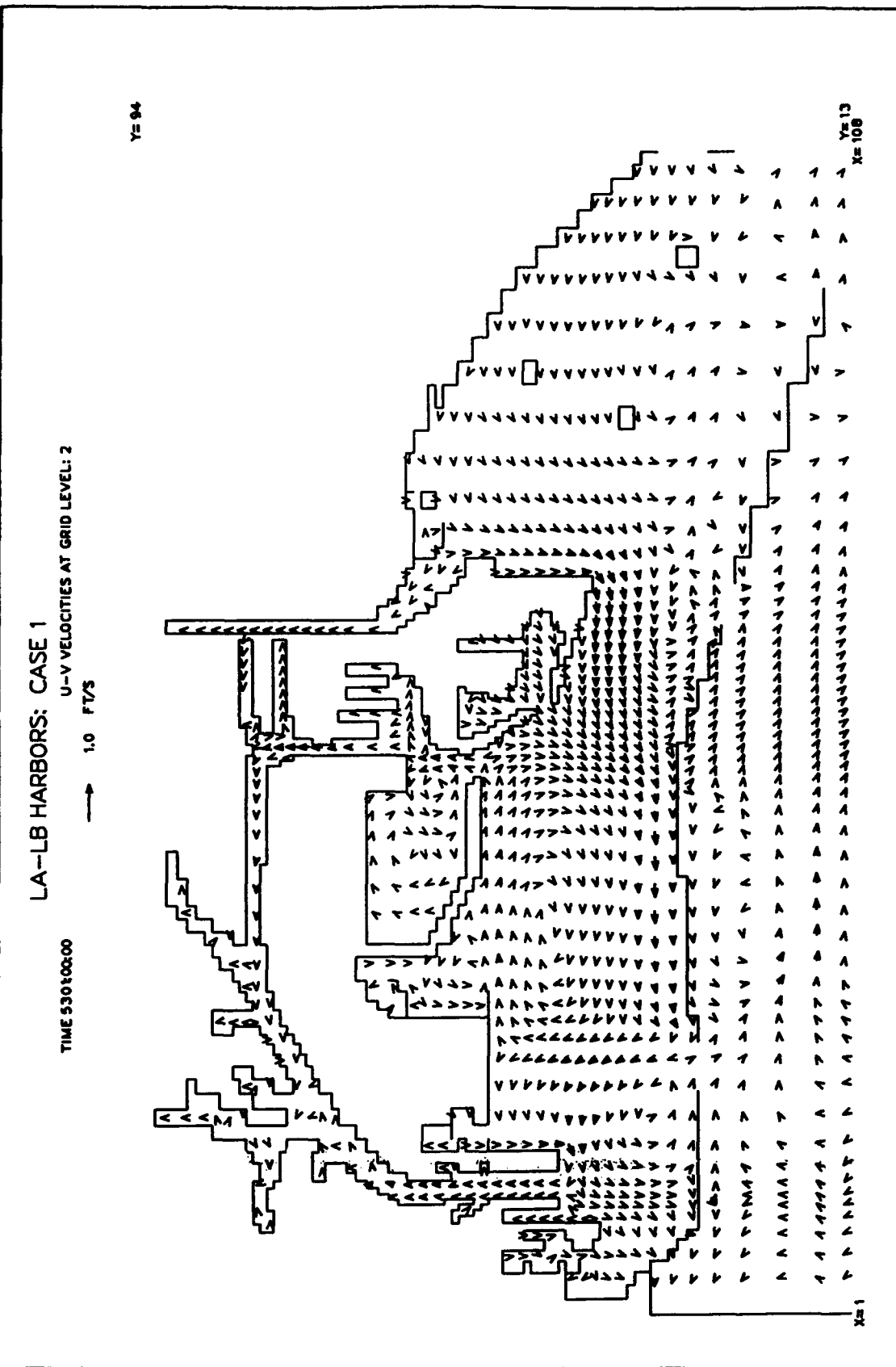


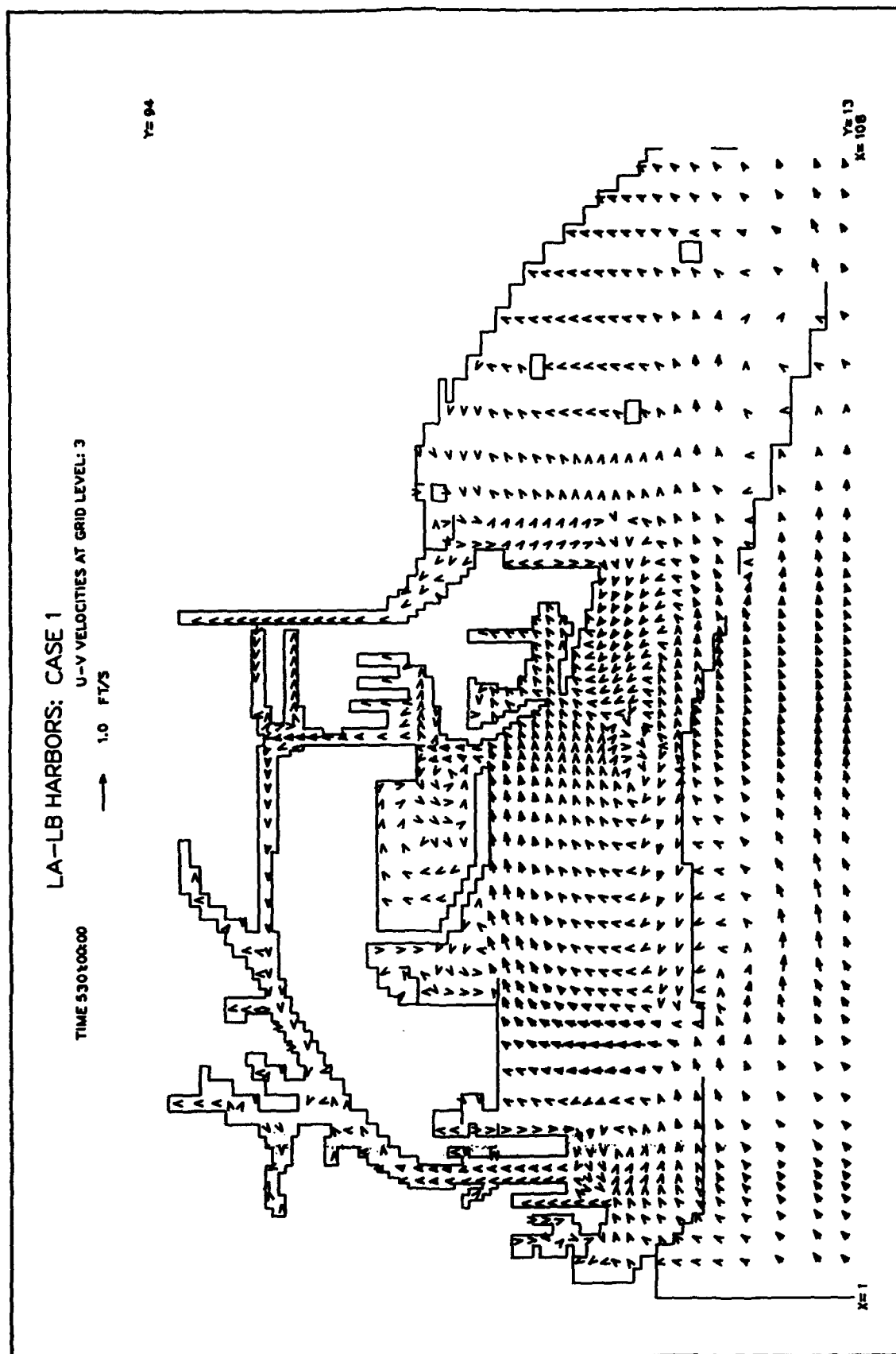












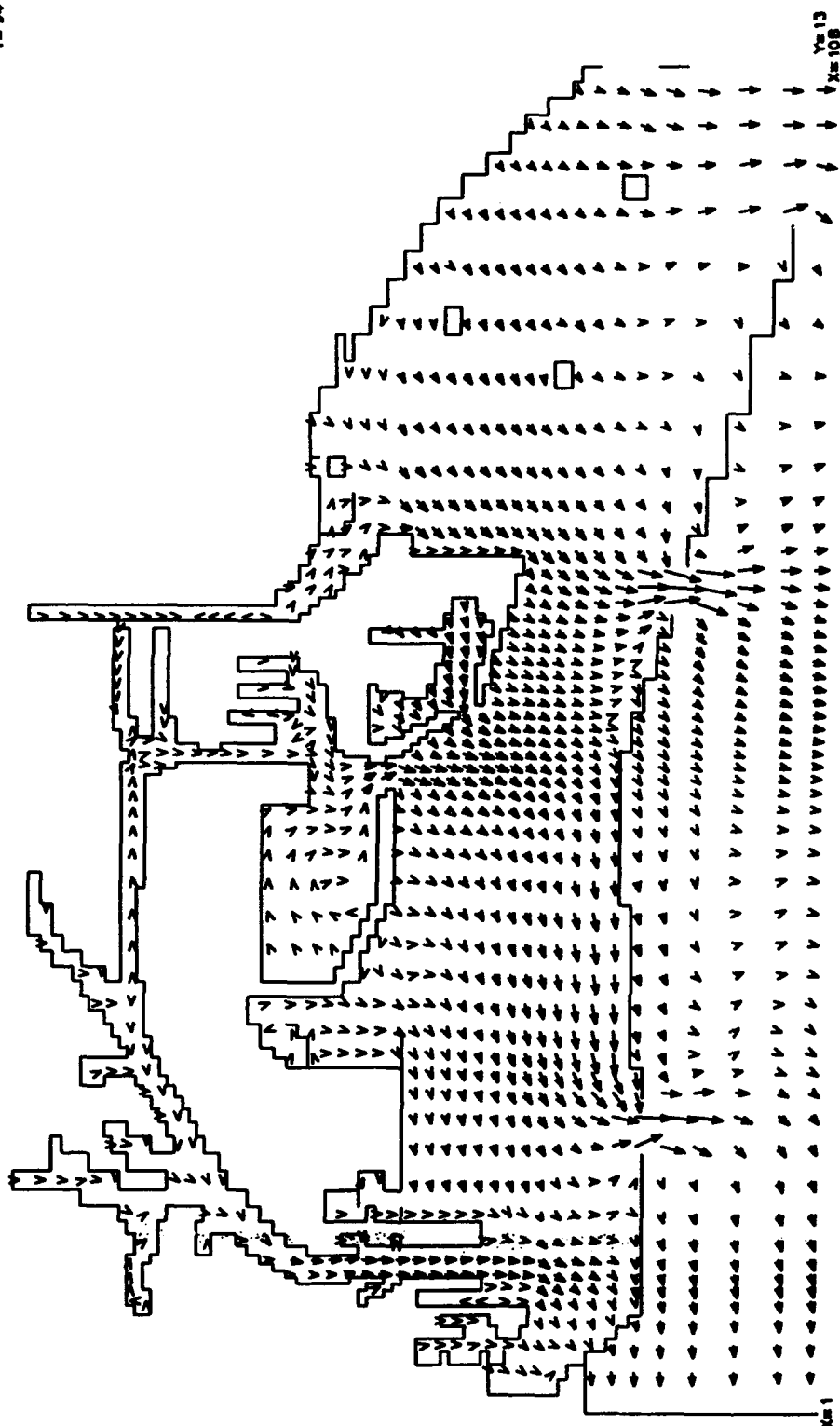
LA-LB HARBORS: CASE 1

TIME 5304:00:00

U-V VELOCITIES AT GRID LEVEL: 1

→ 1.0 FT/S

Y= 94



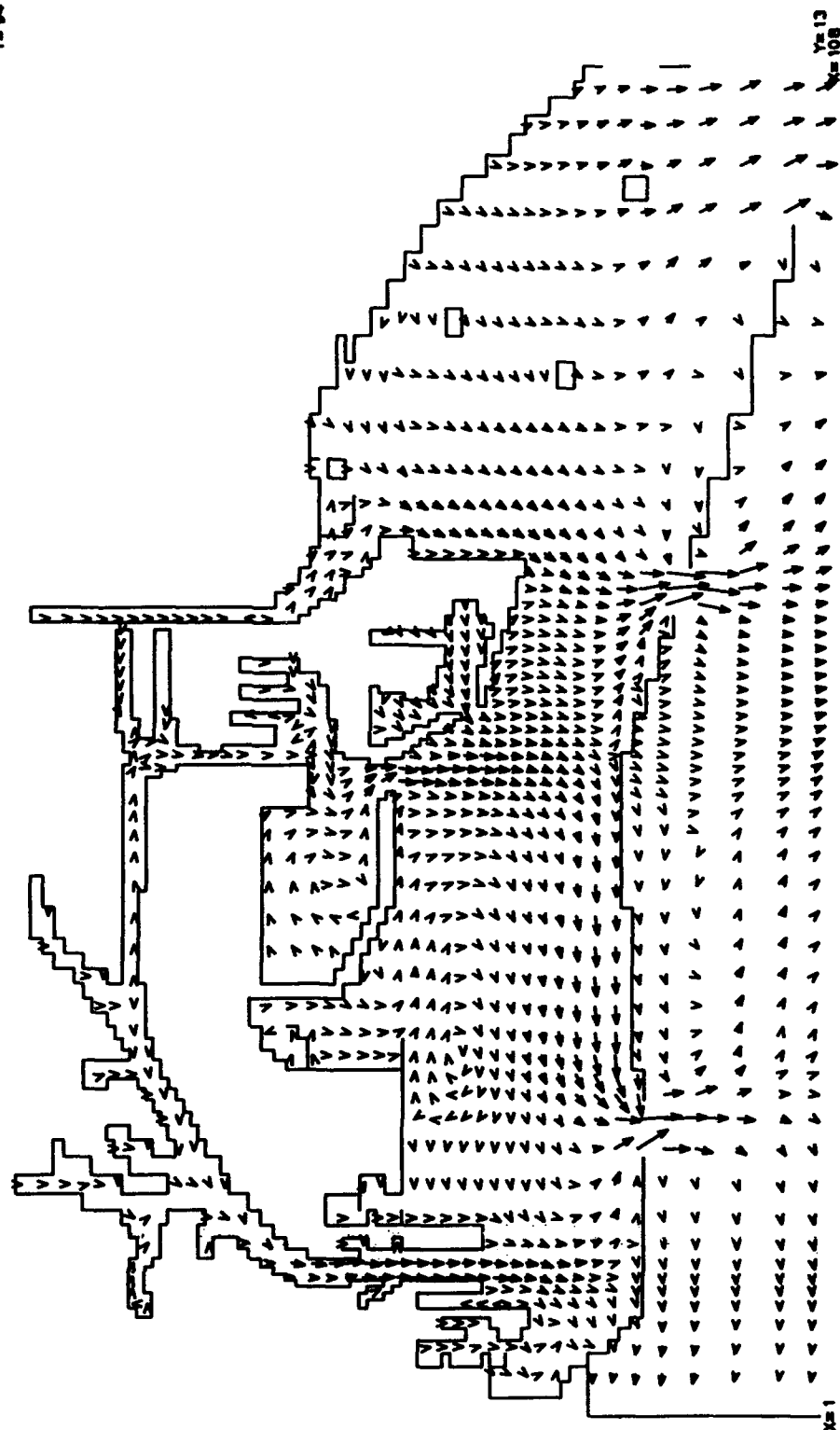
LA-LB HARBORS: CASE 1

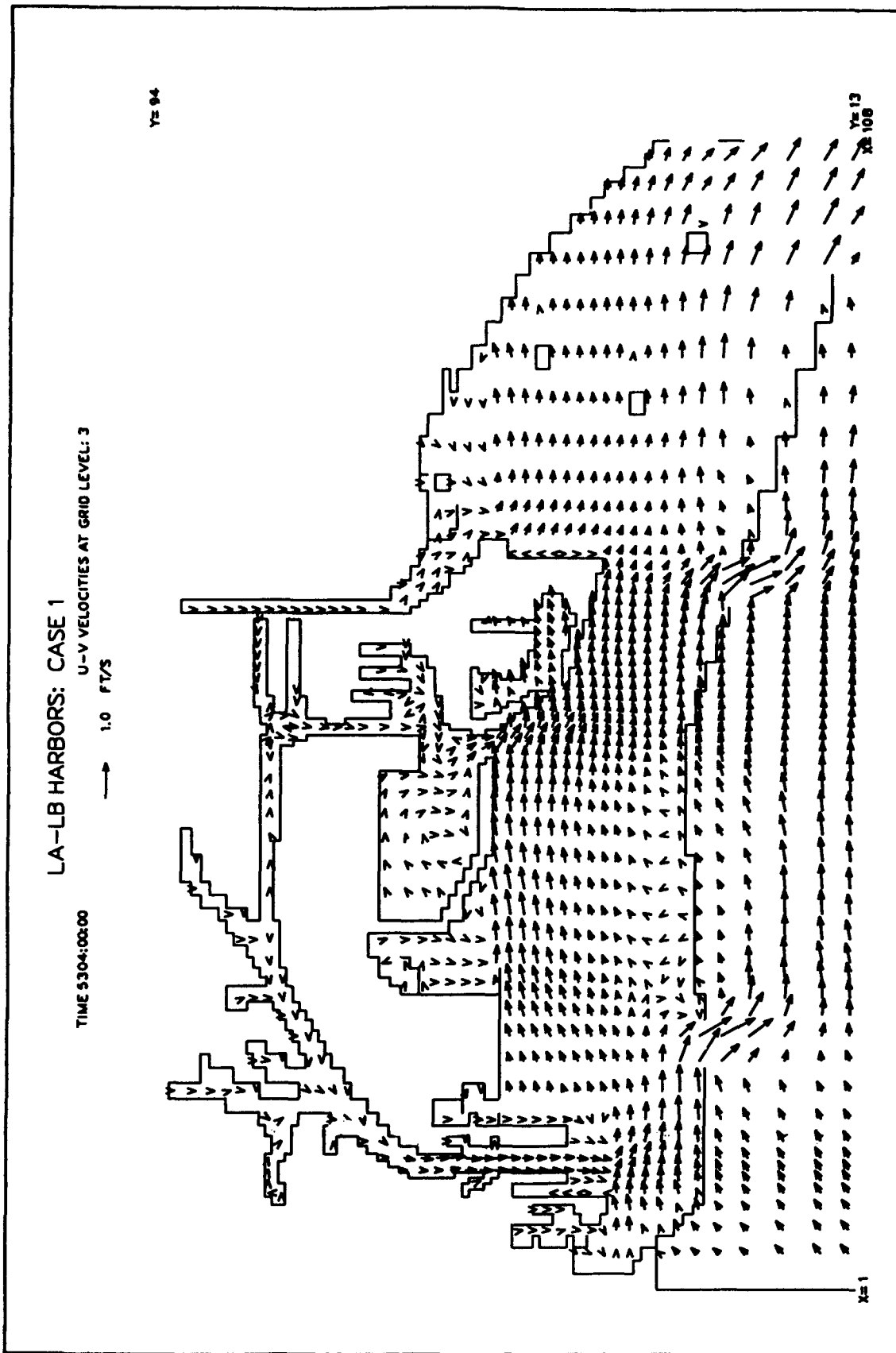
TIME 2304:00:00

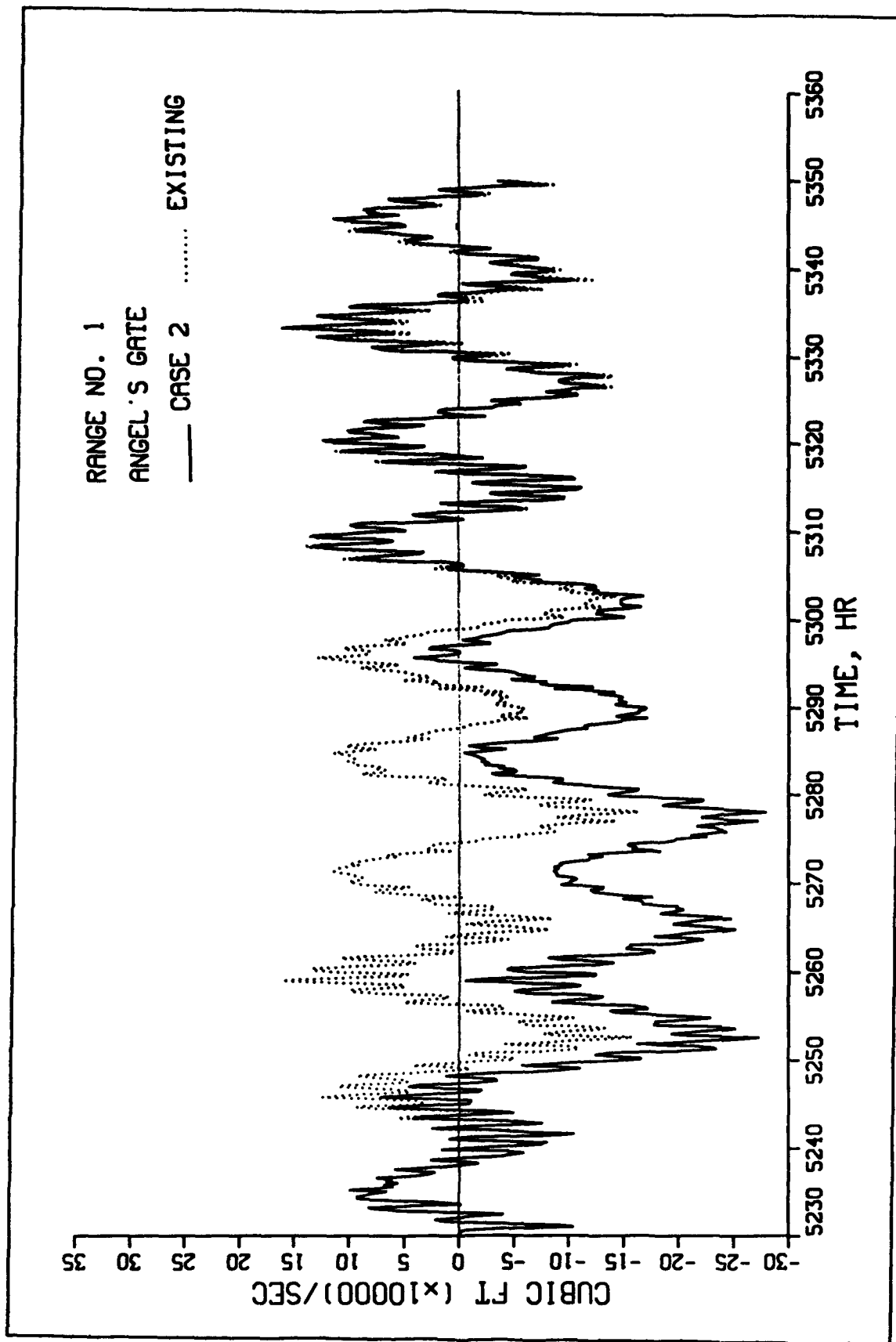
U-V VELOCITIES AT GRID LEVEL: 2

→ 1.0 FT/S

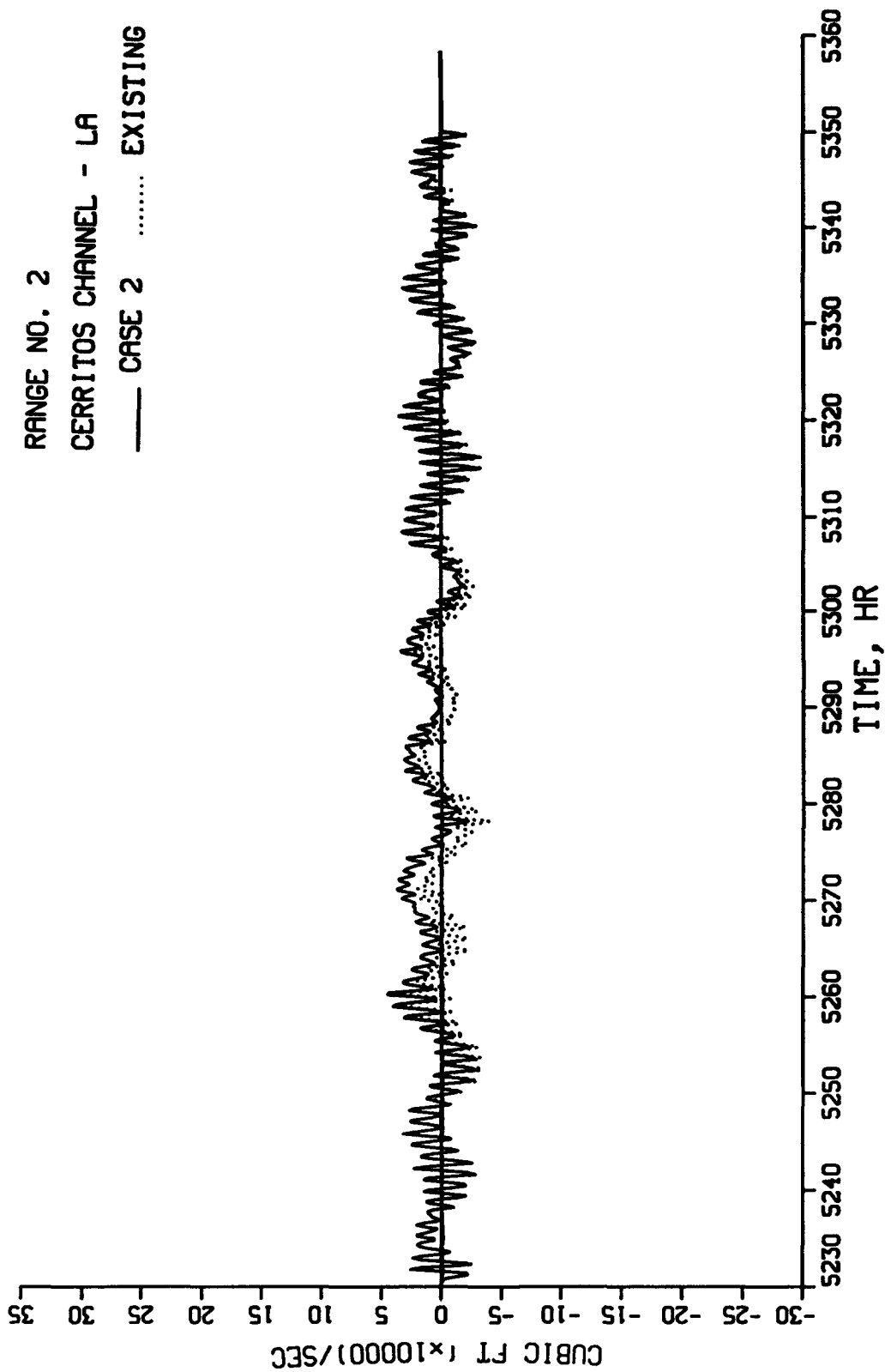
Y= 94



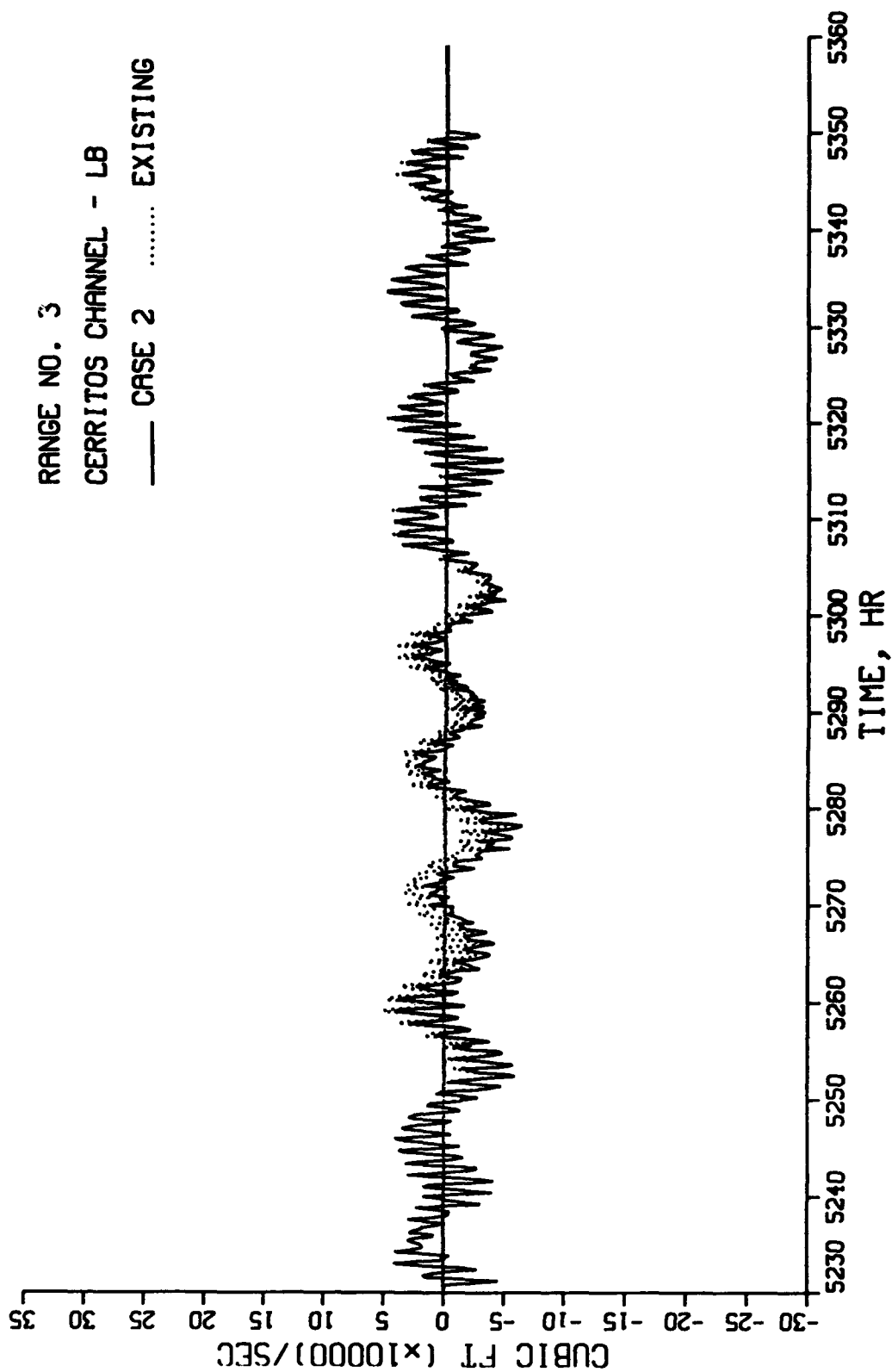




RANGE NO. 2
CERRITOS CHANNEL - LA
— CASE 2 EXISTING



RANGE NO. 3
CERRITOS CHANNEL - LB
— CASE 2 EXISTING



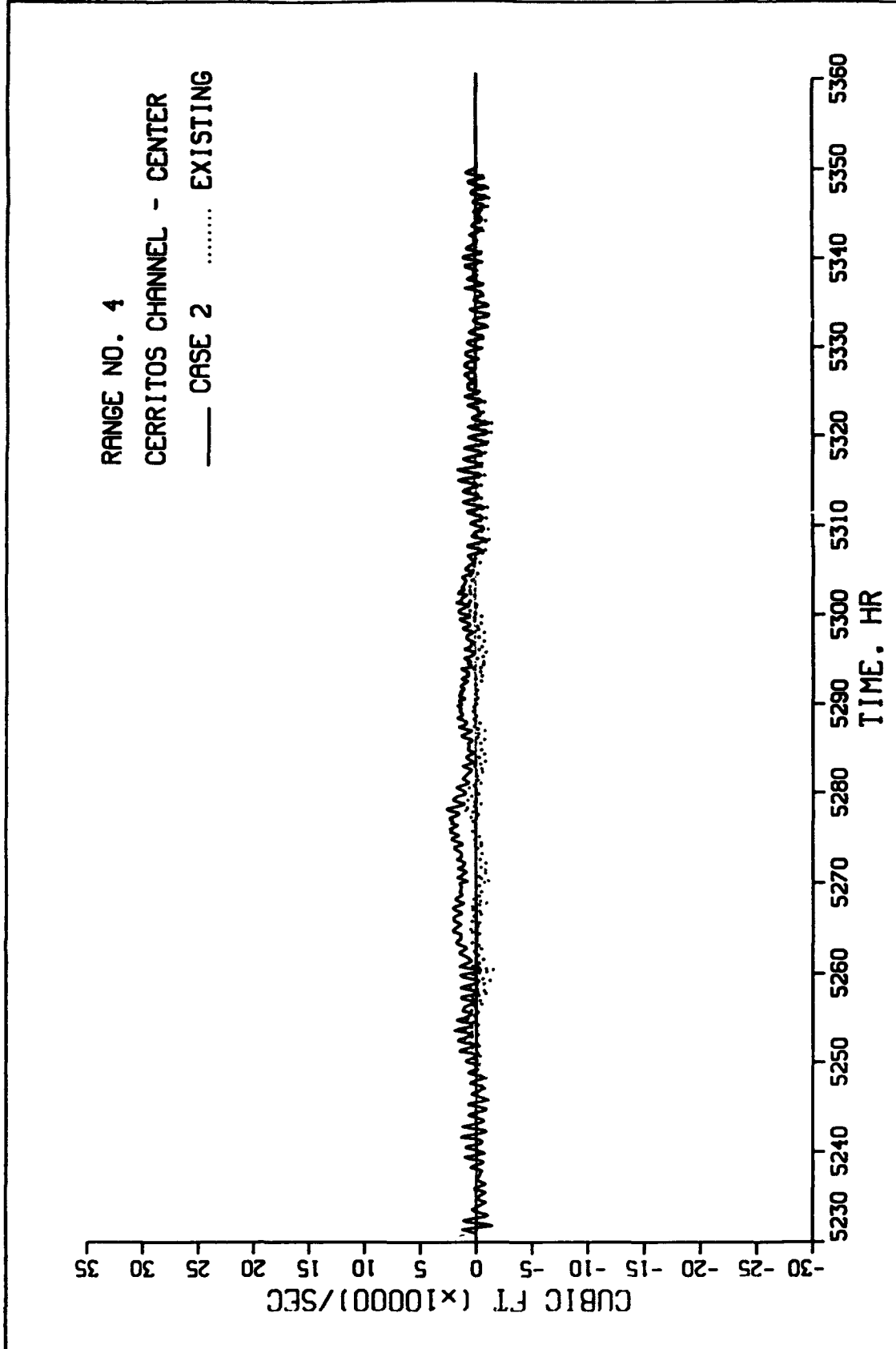
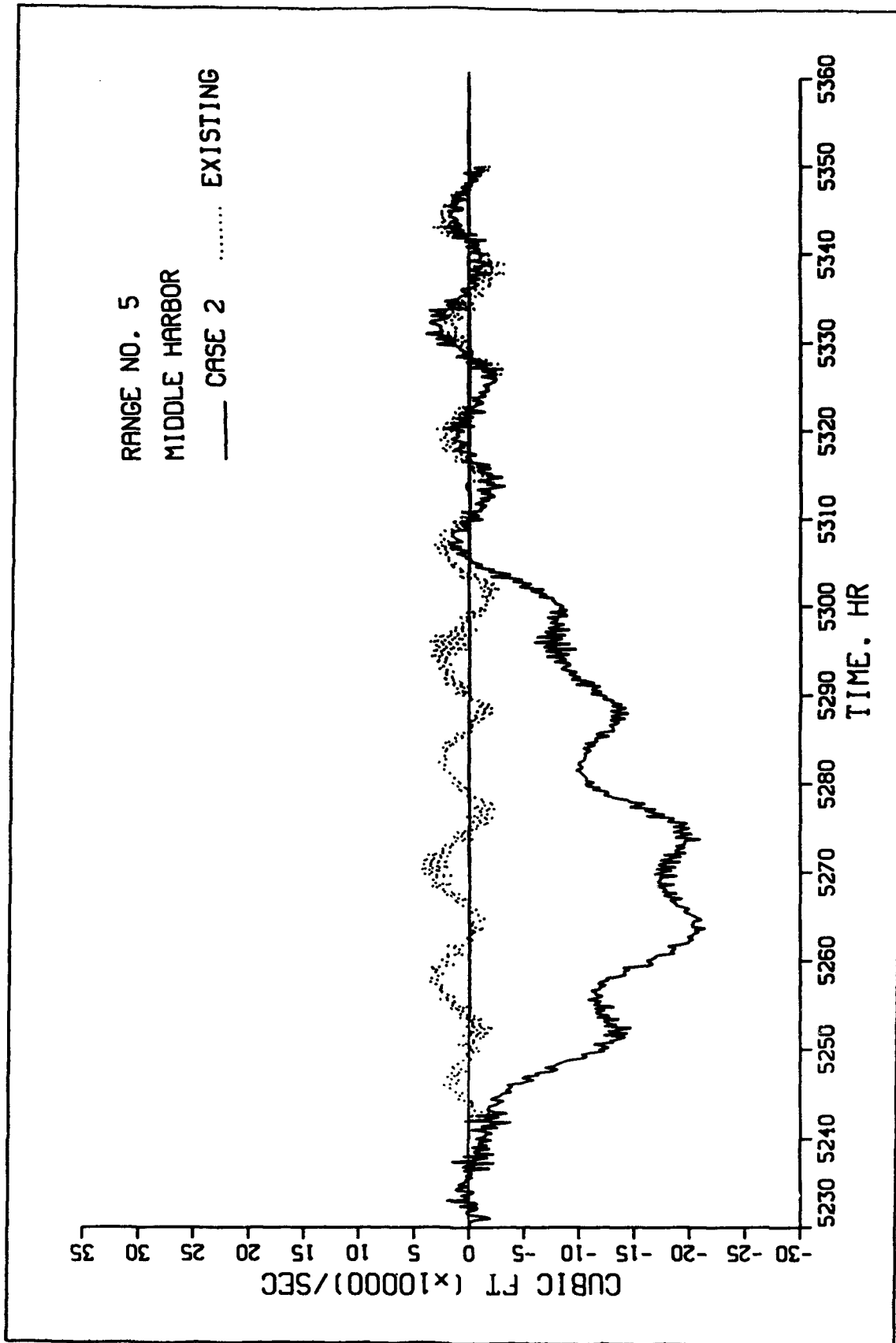
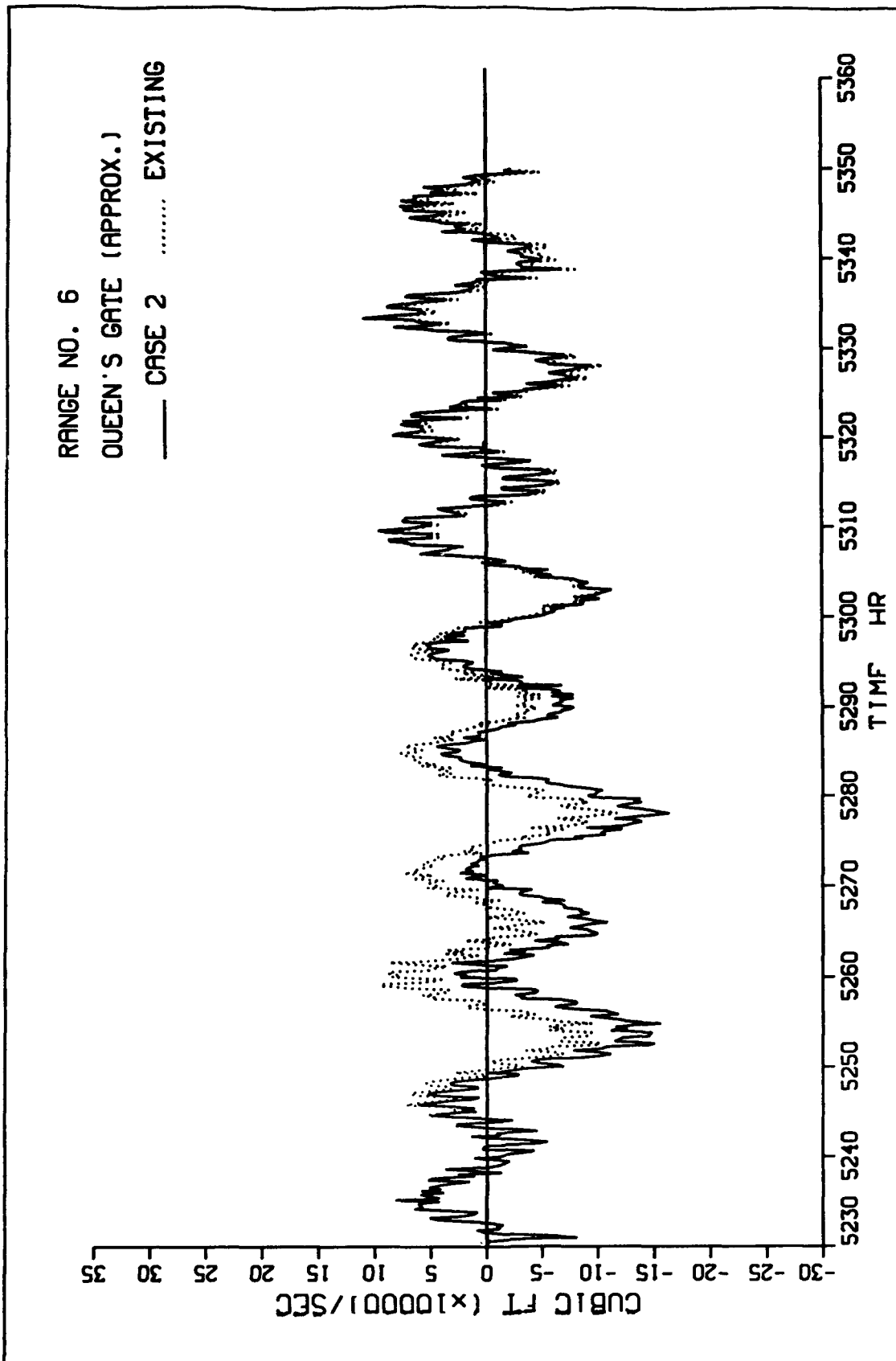
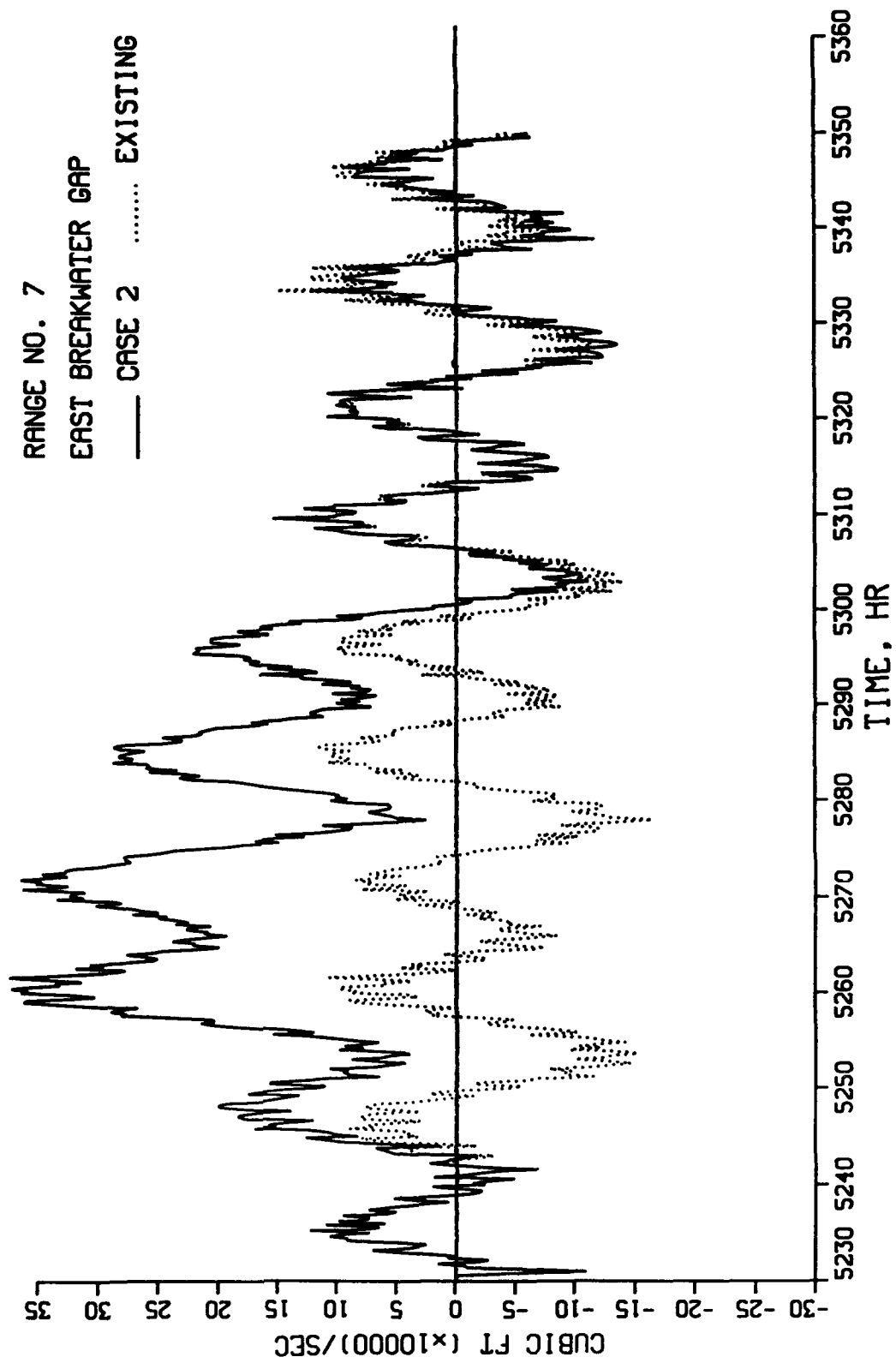


PLATE 74

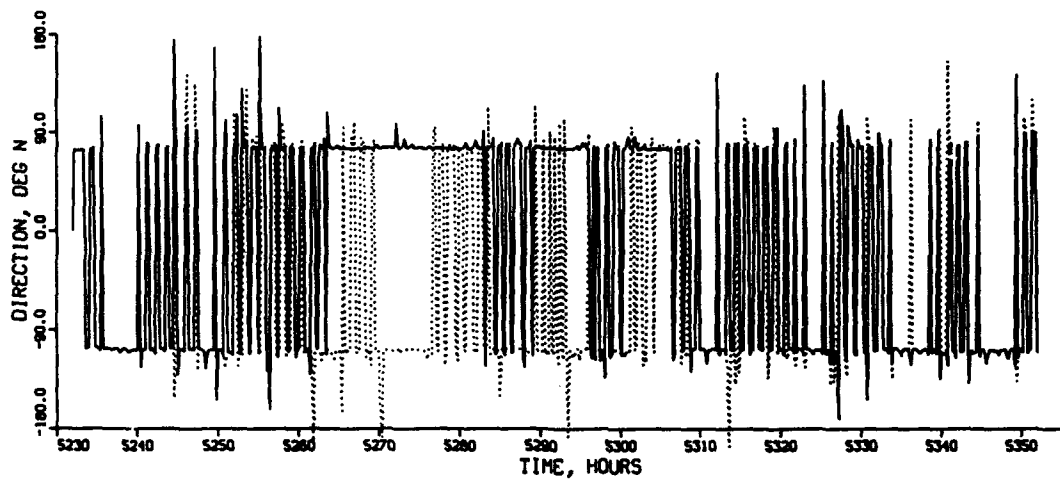
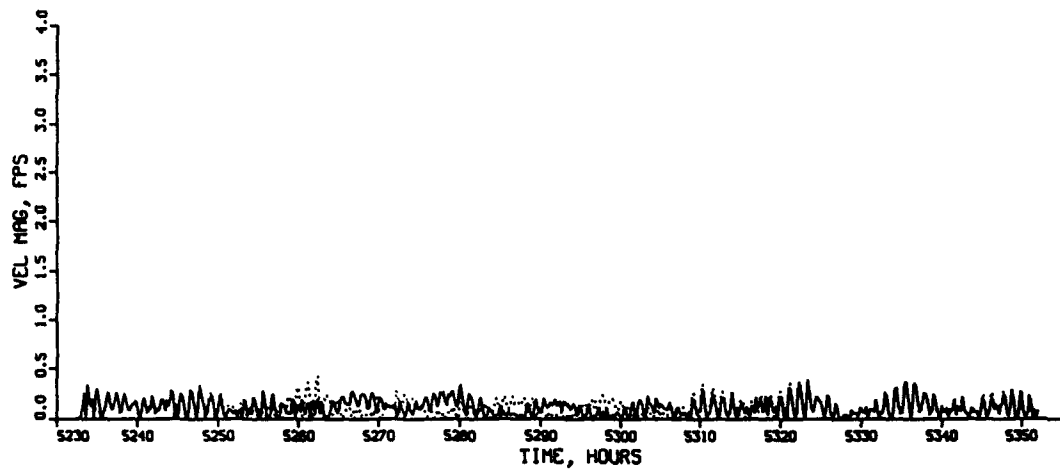




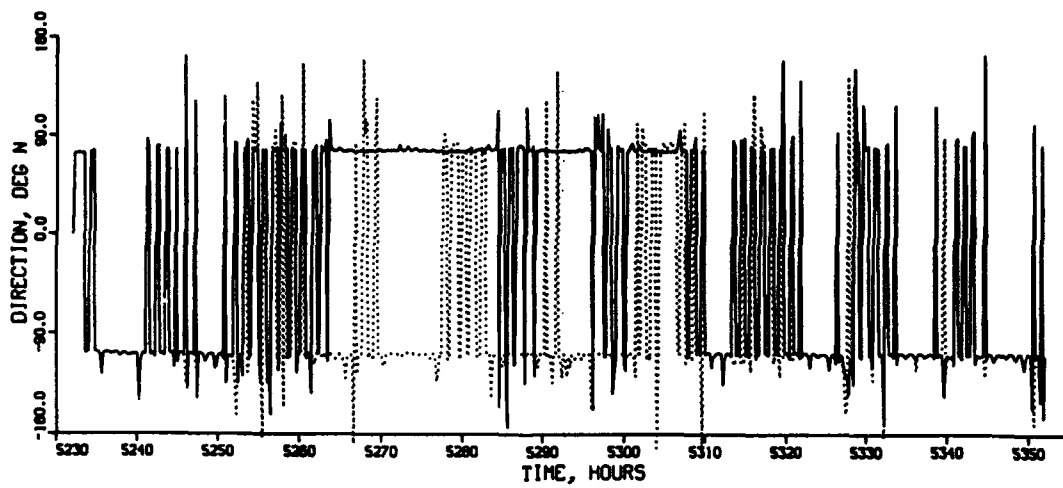
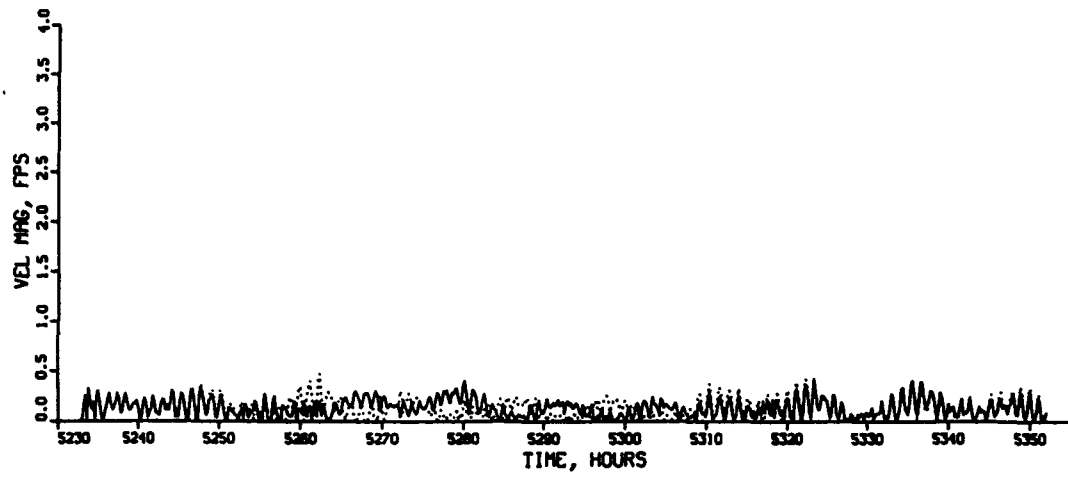
RANGE NO. 7
EAST BREAKWATER GAP
— CASE 2 EXISTING

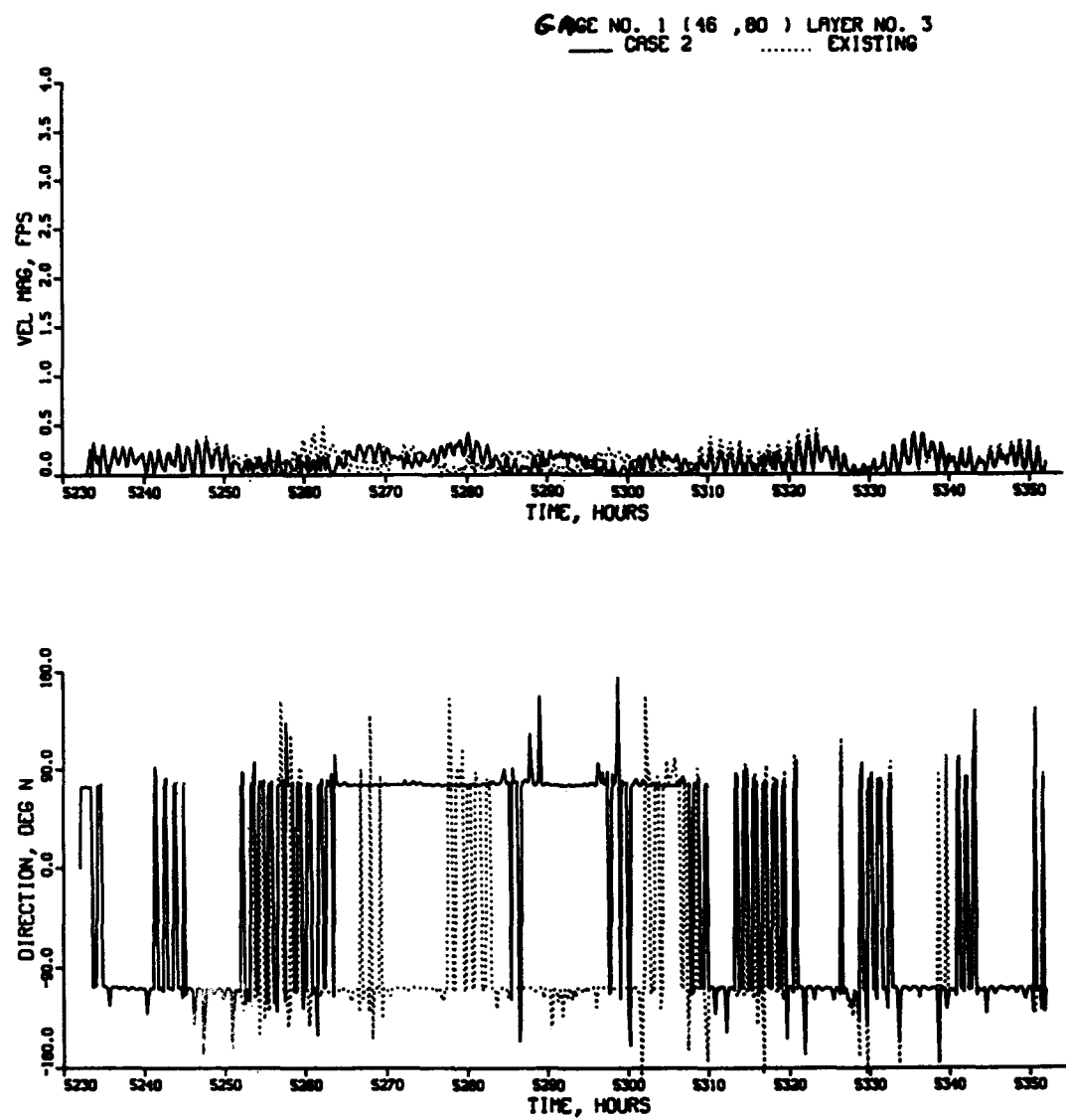


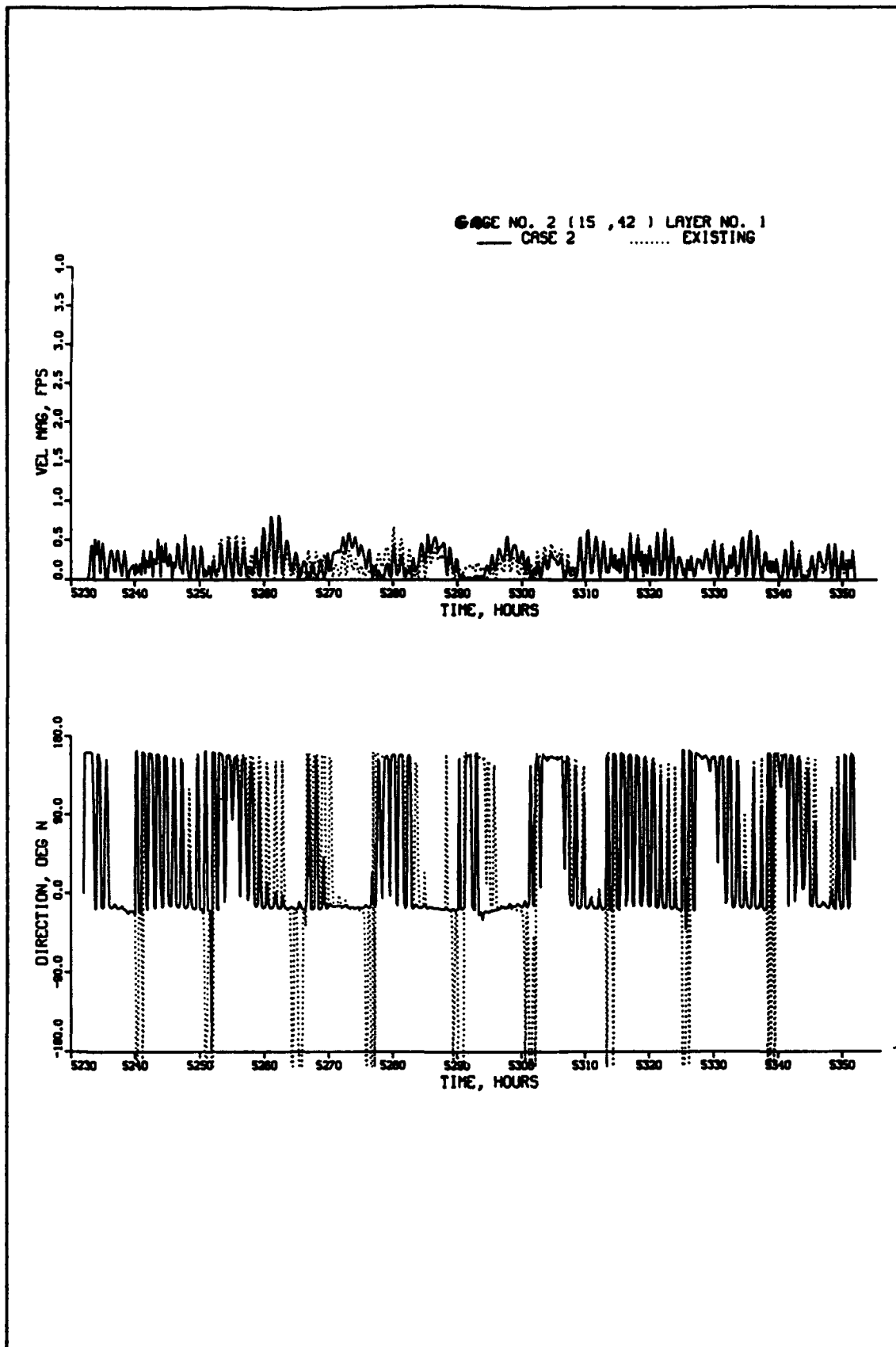
CAGE NO. 1 (16, 80) LAYER NO. 1
— CASE 2 EXISTING

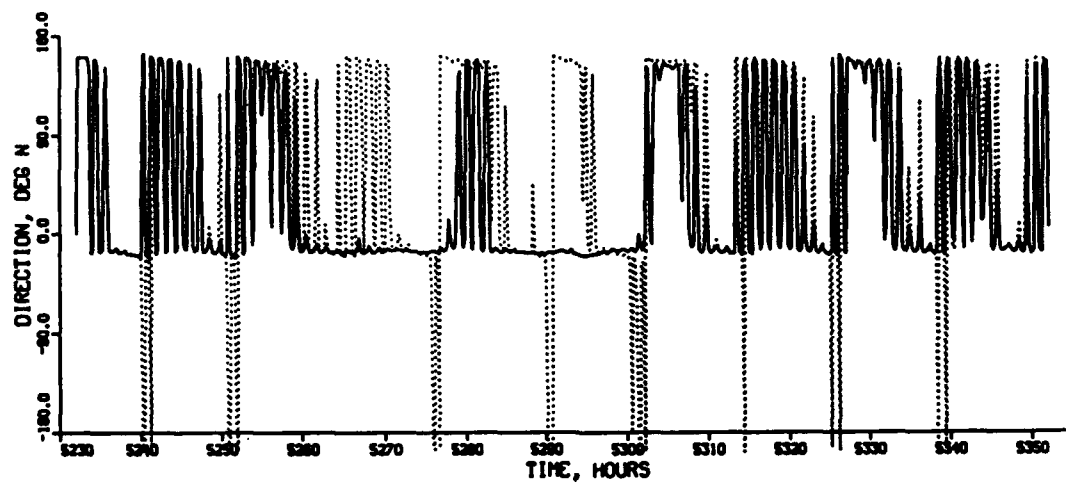
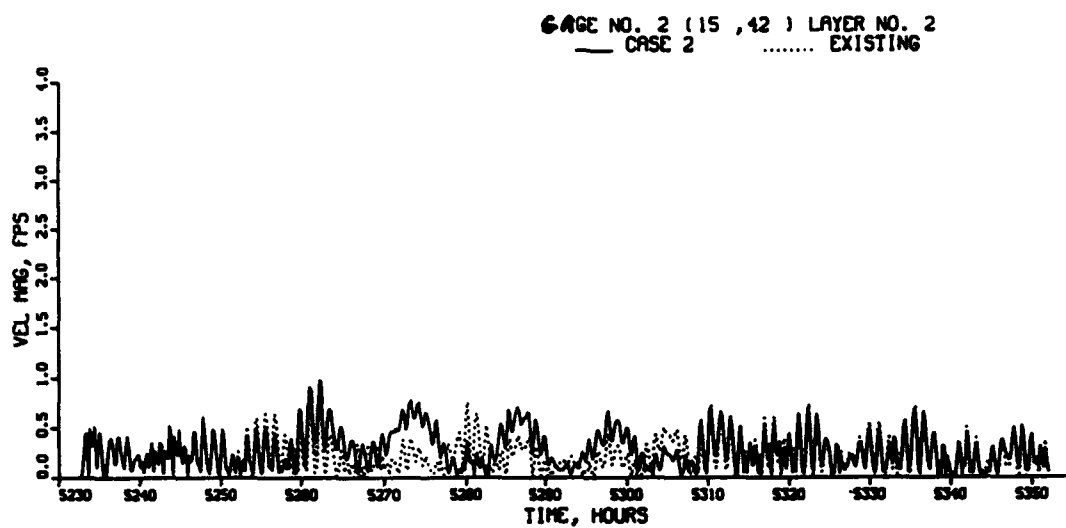


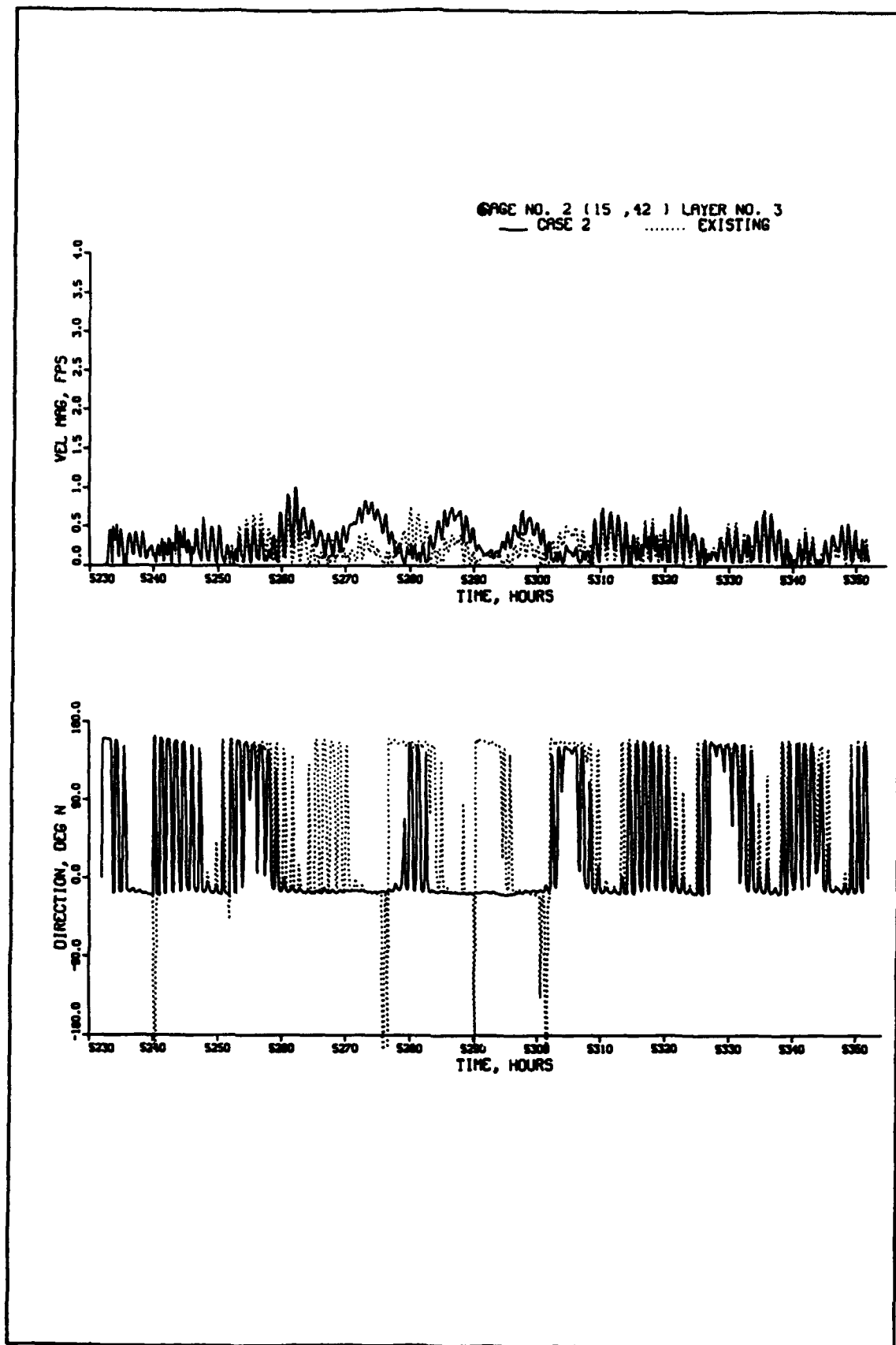
GAGE NO. 1 (16 , 80) LAYER NO. 2
— CASE 2 EXISTING

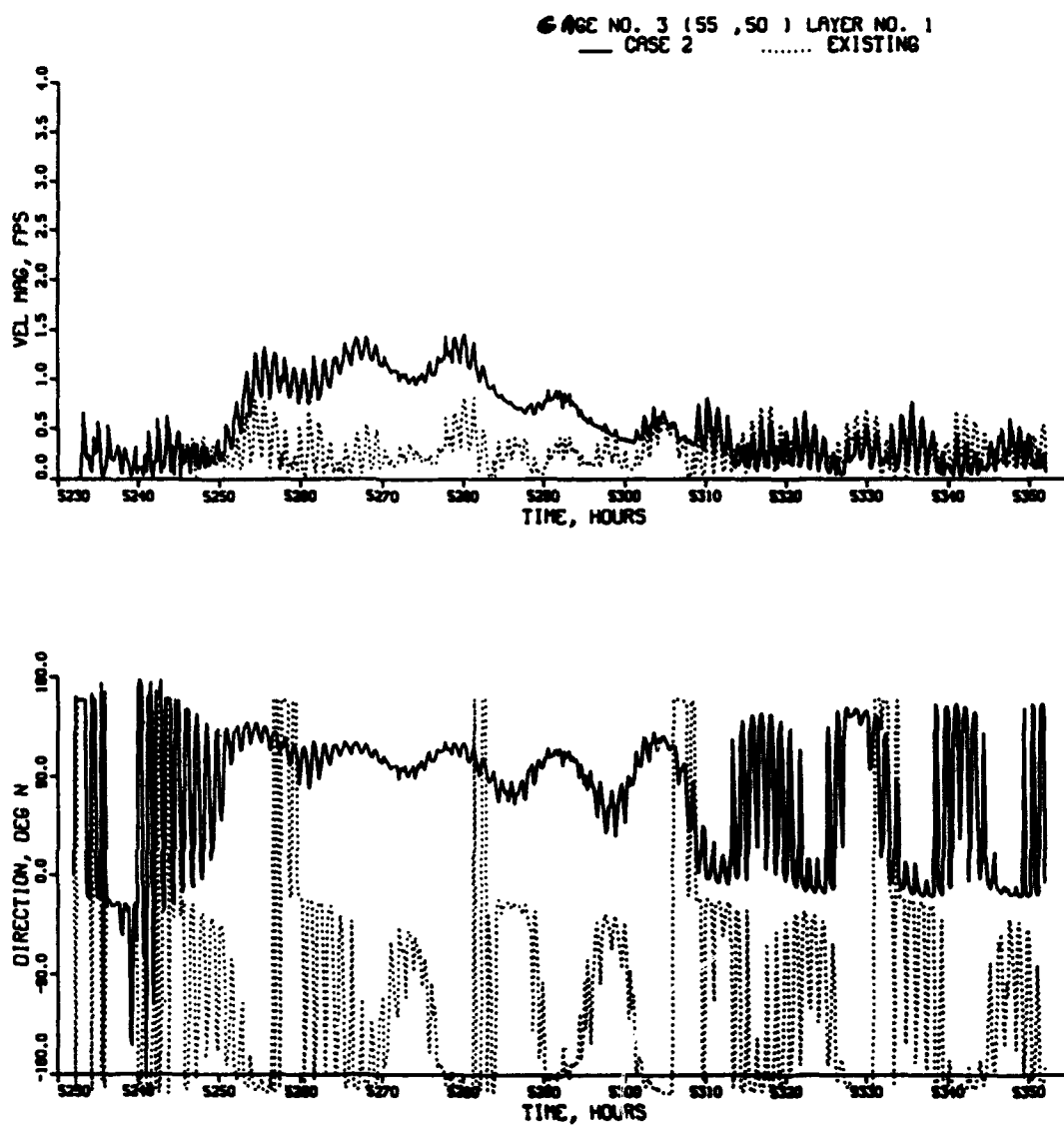


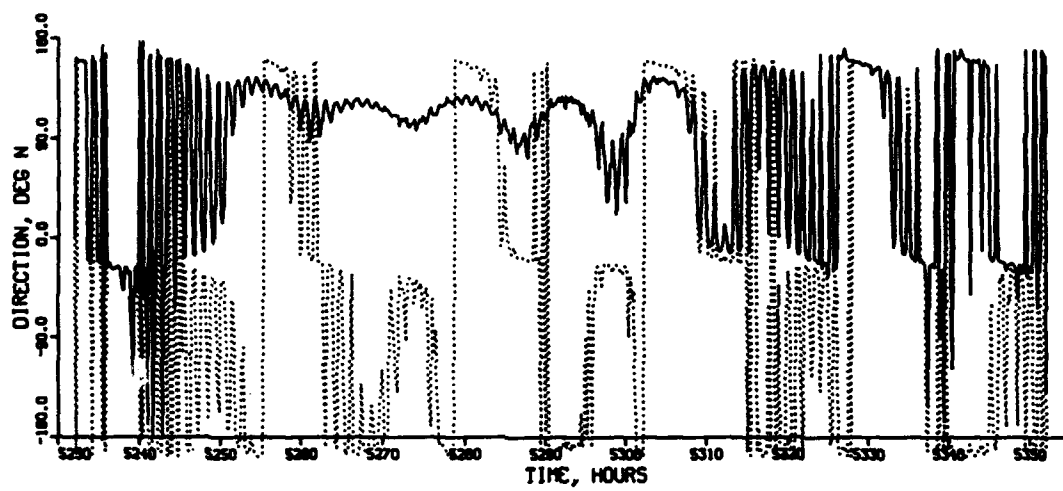
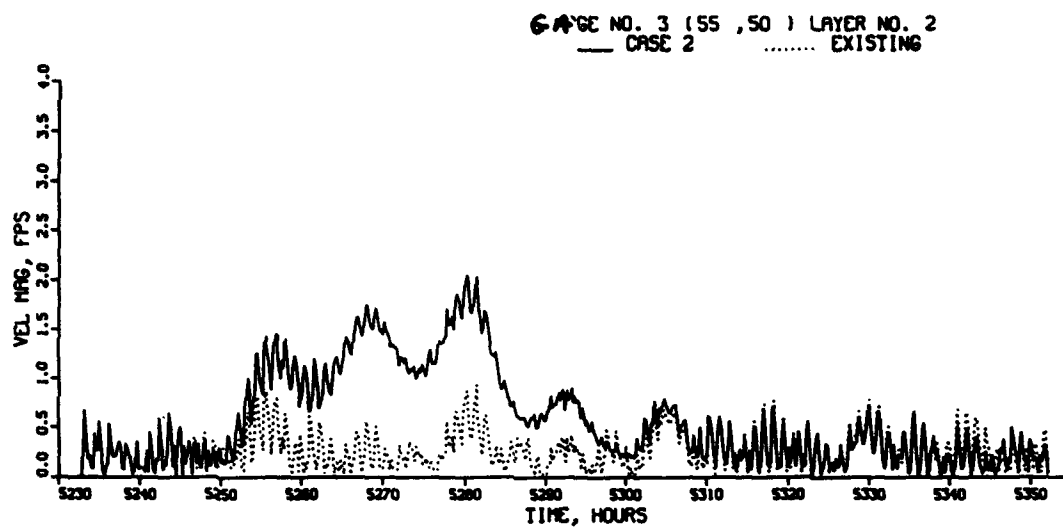


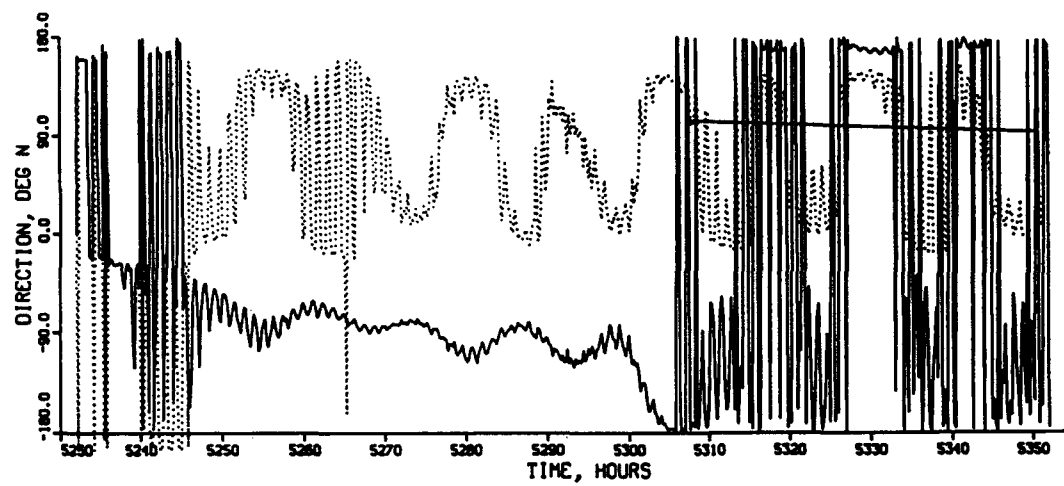
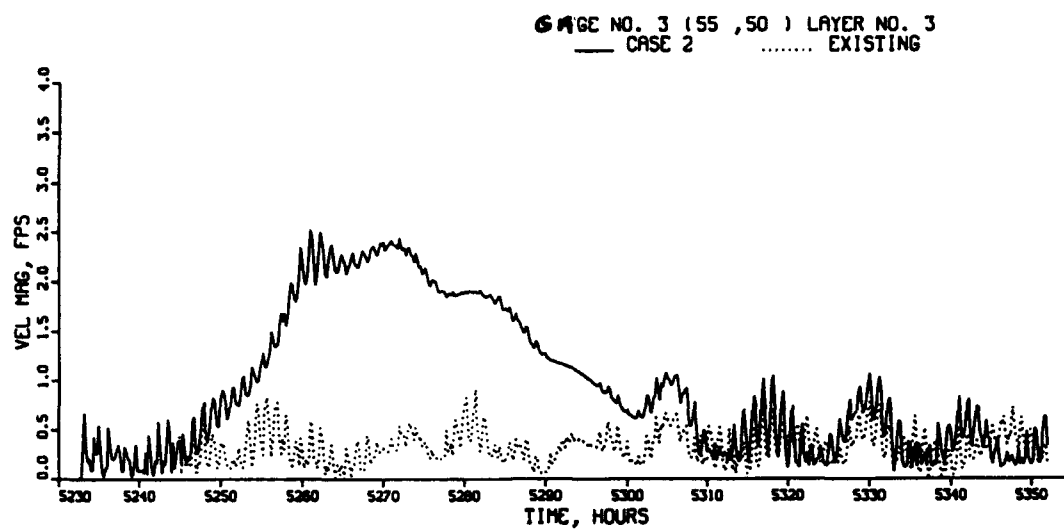


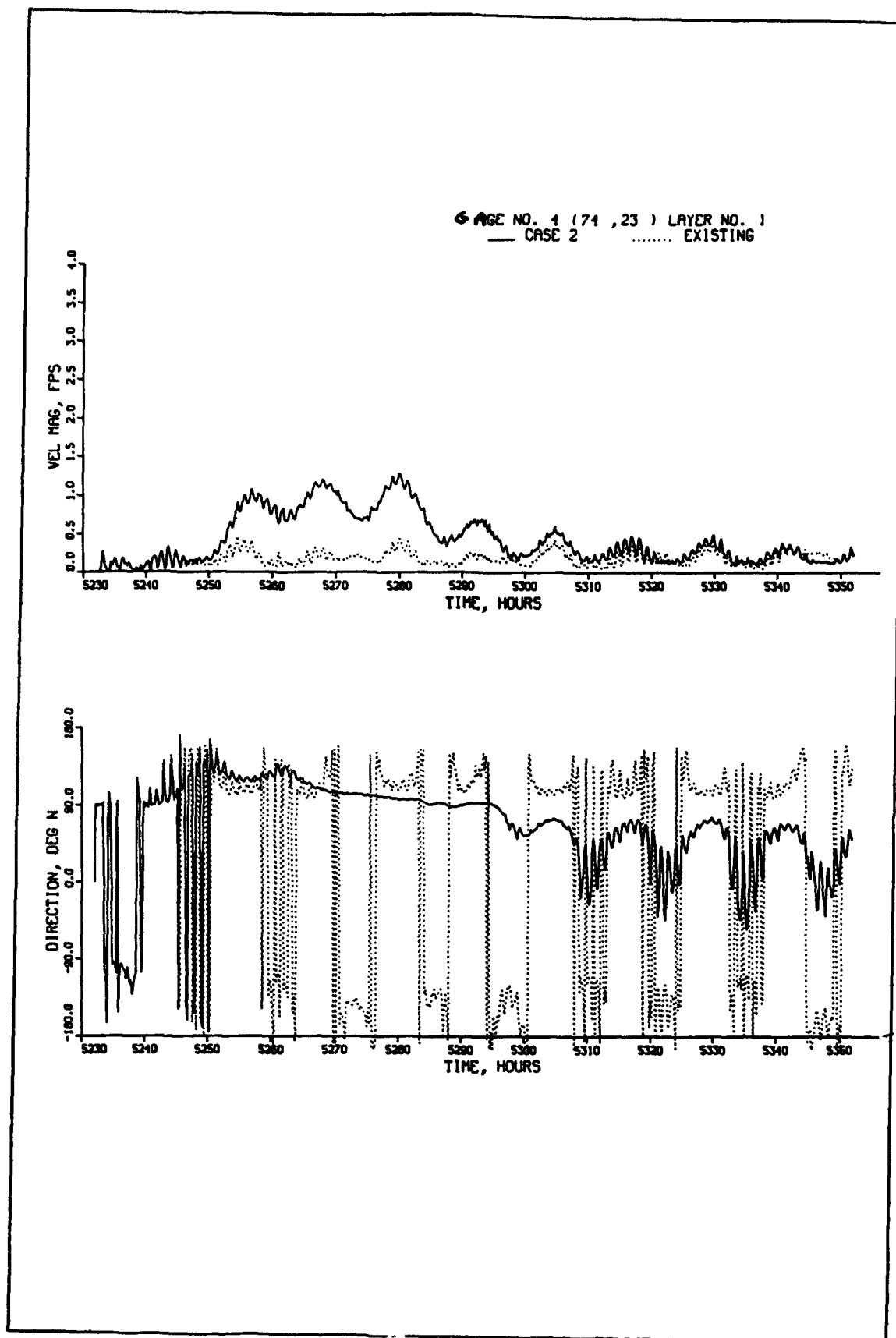


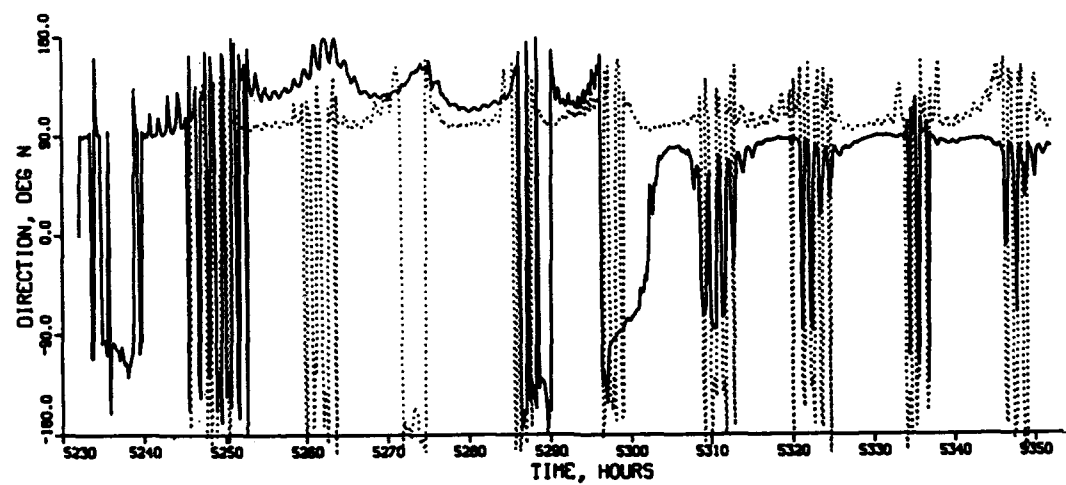
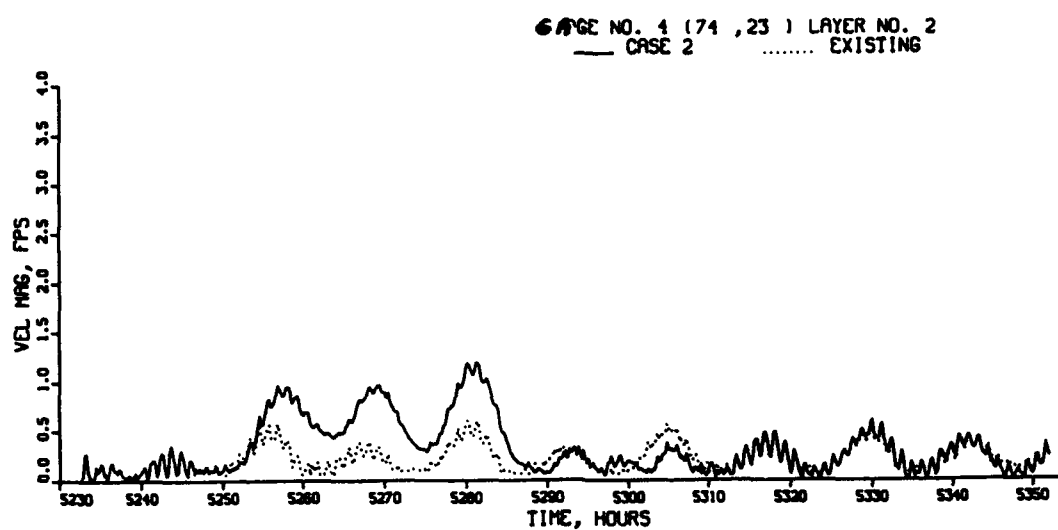


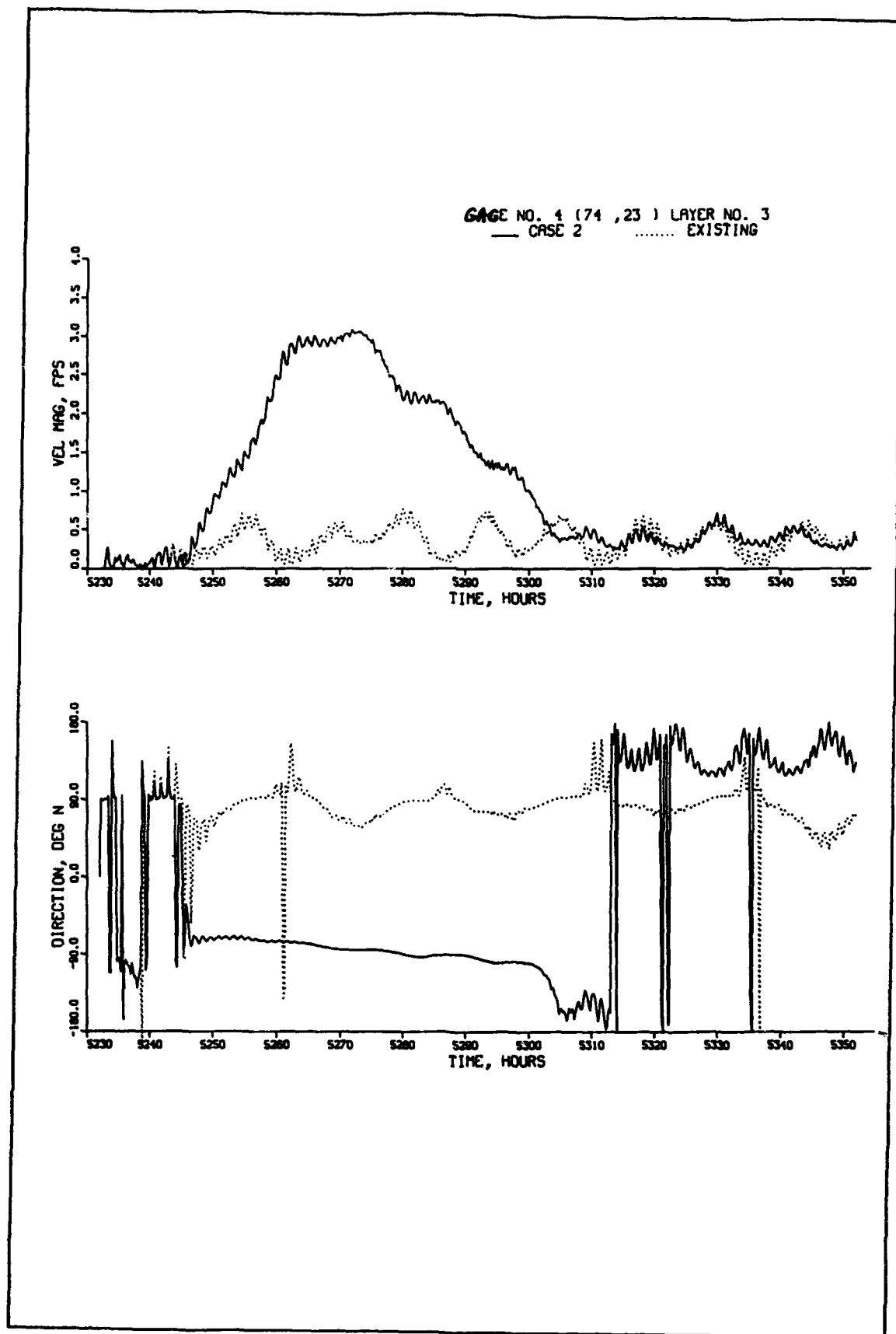


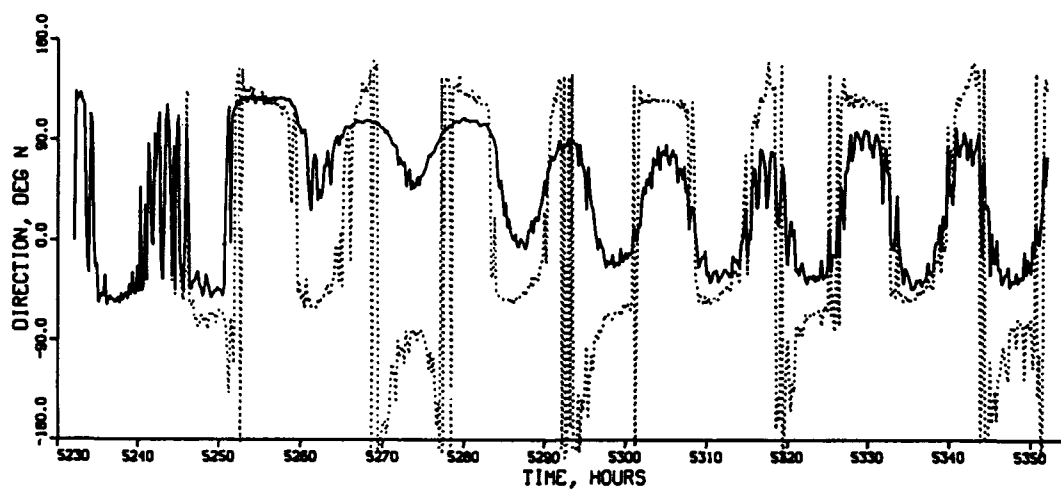
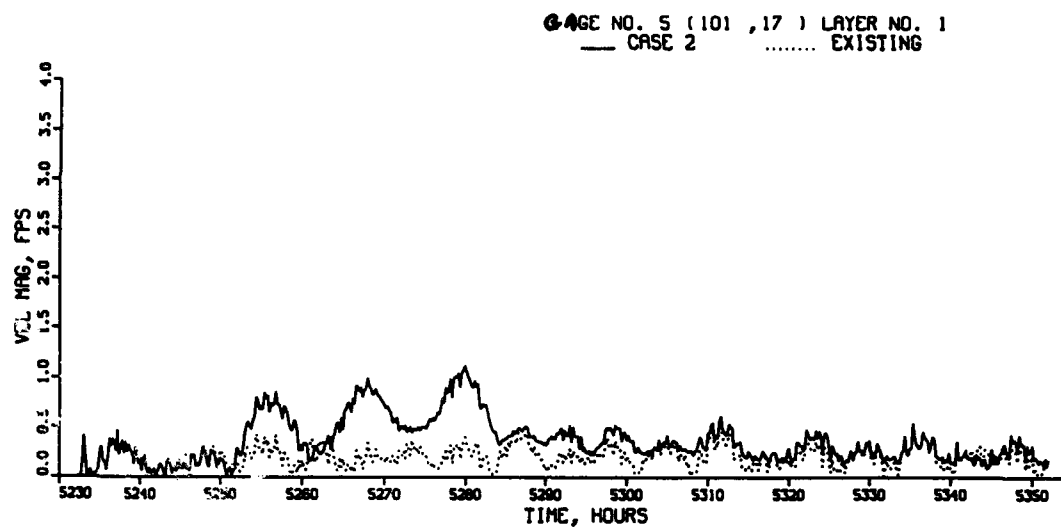




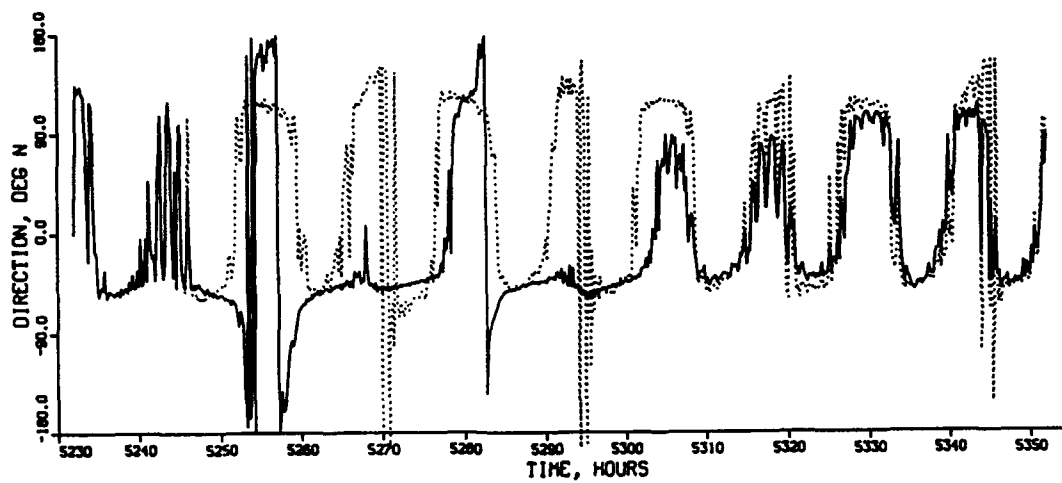
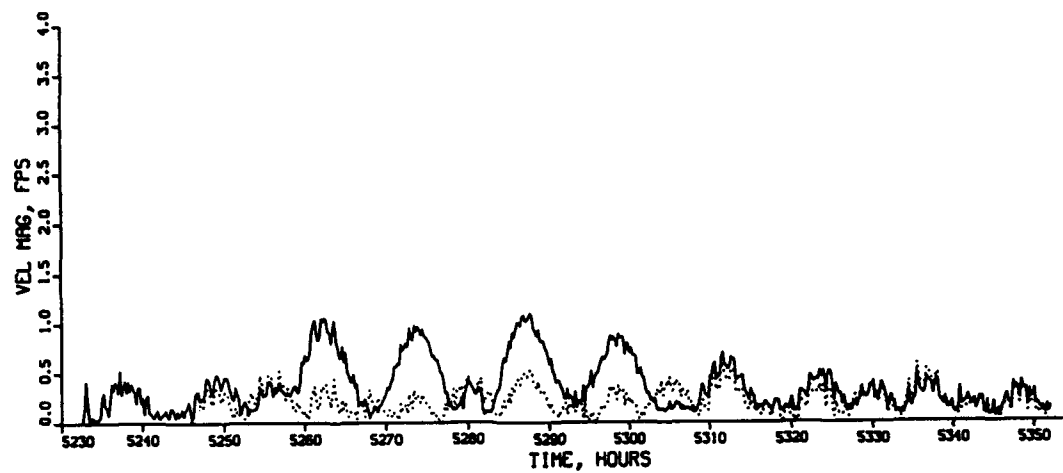


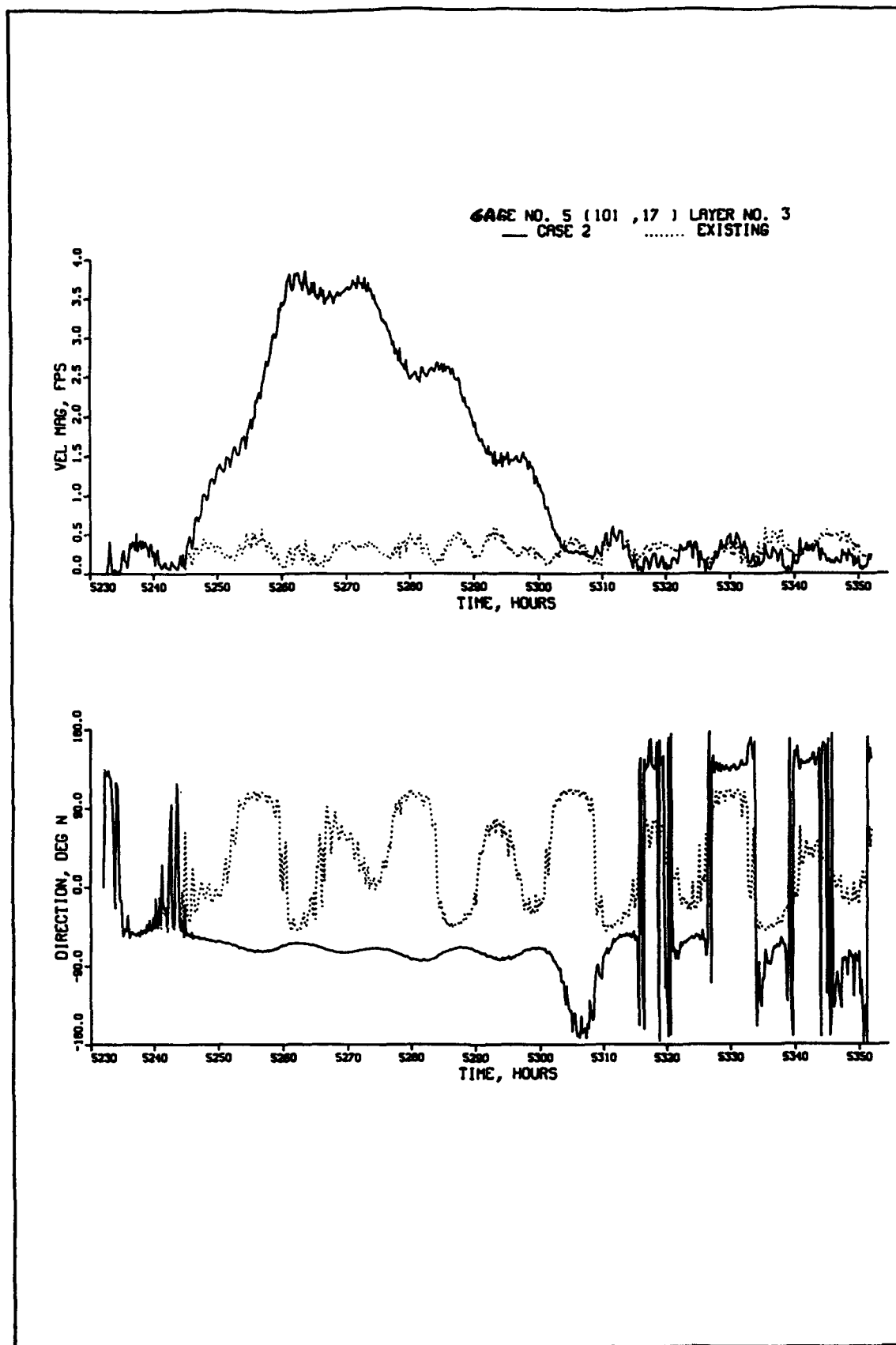




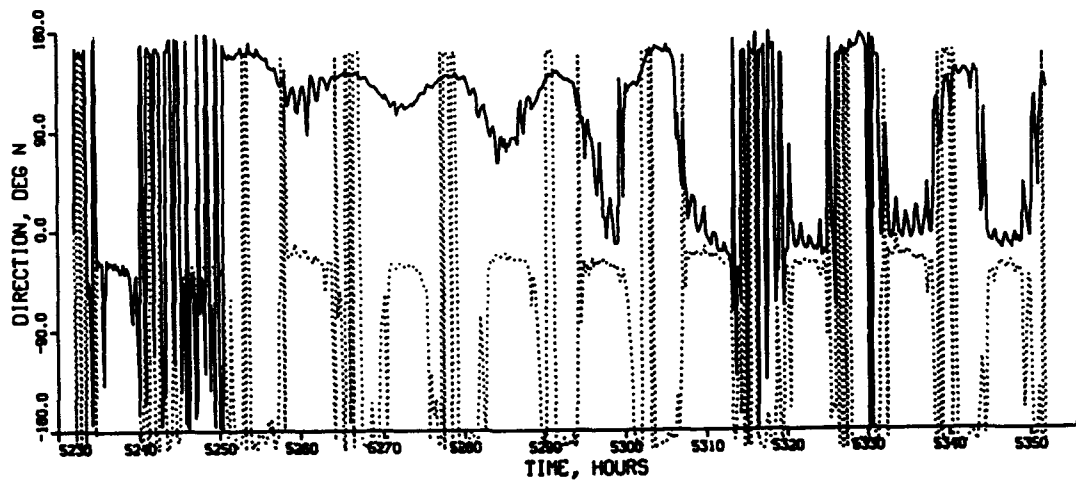
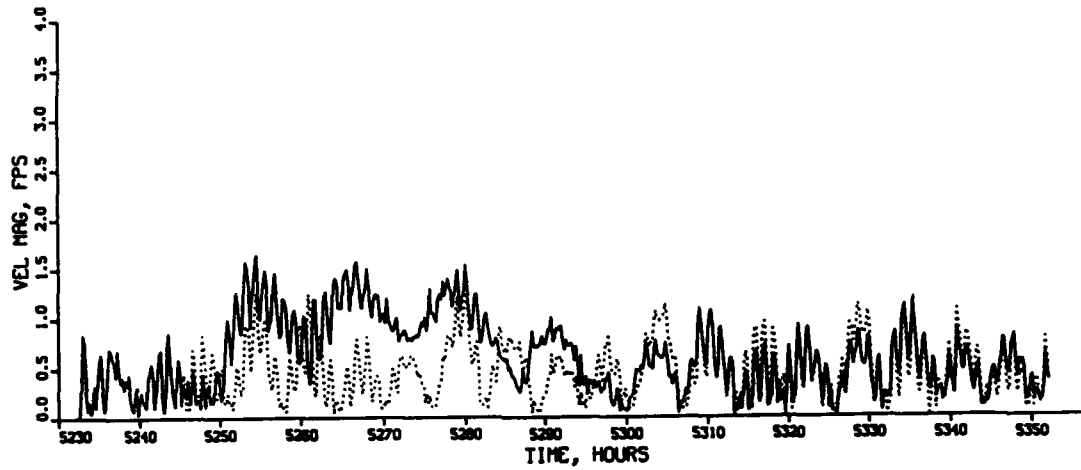


CAGE NO. 5 (101 , 17) LAYER NO. 2
— CASE 2 EXISTING

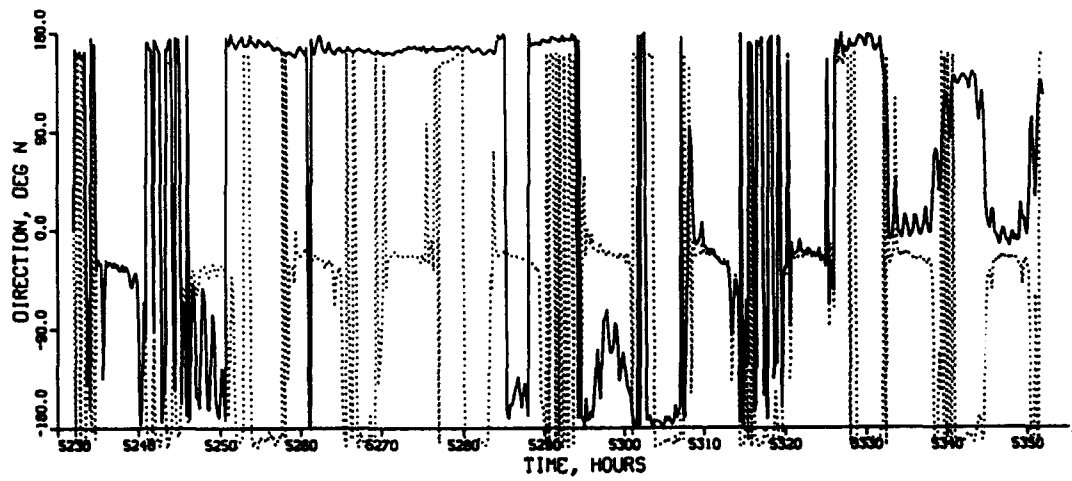
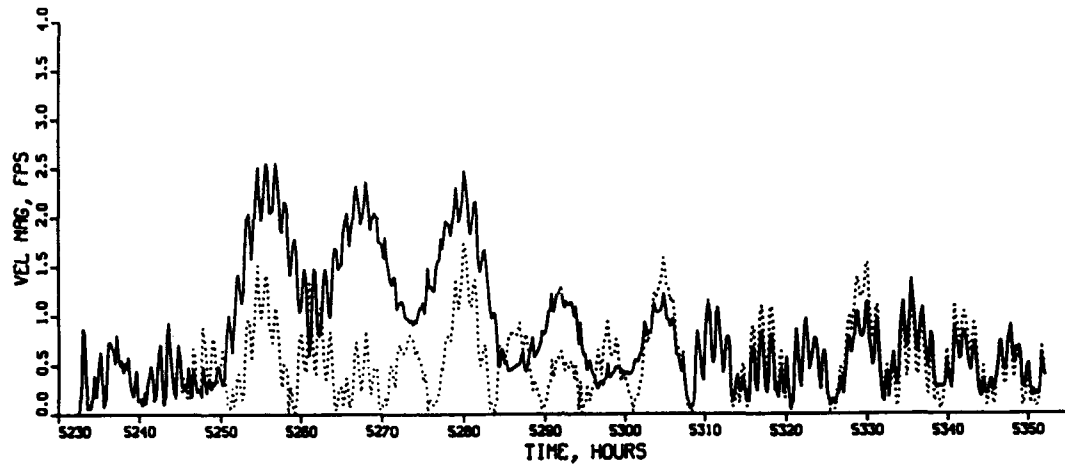


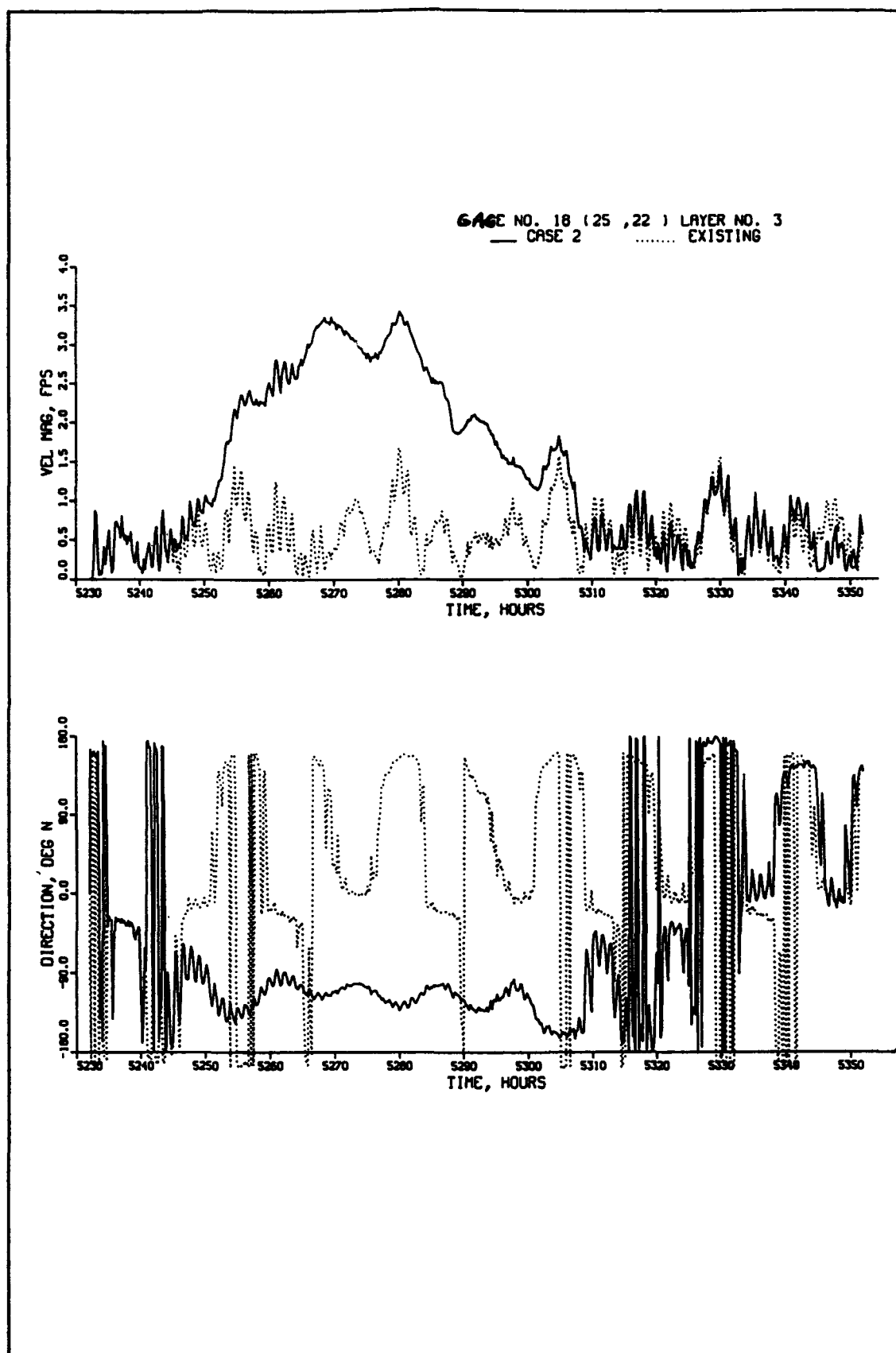


GAGE NO. 18 (25 , 22) LAYER NO. 1
— CASE 2 EXISTING

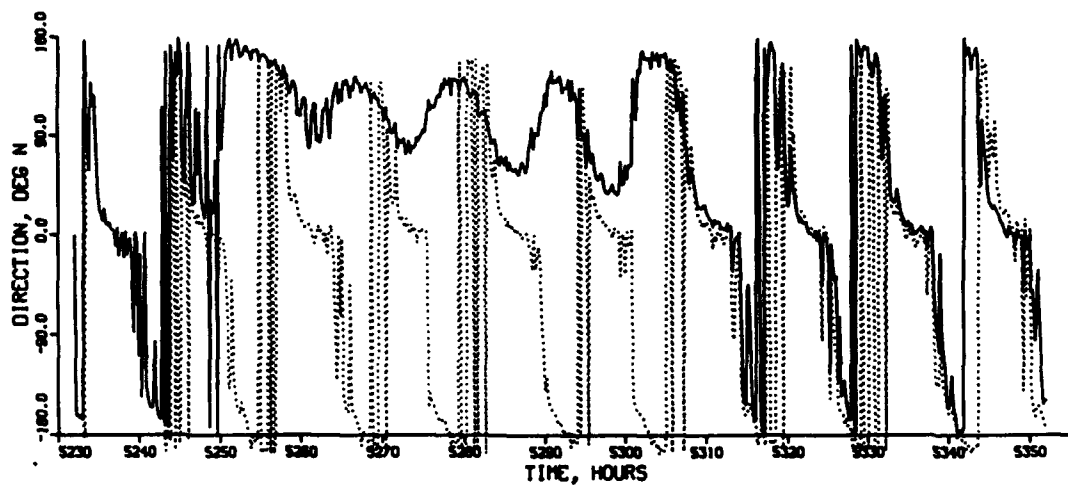
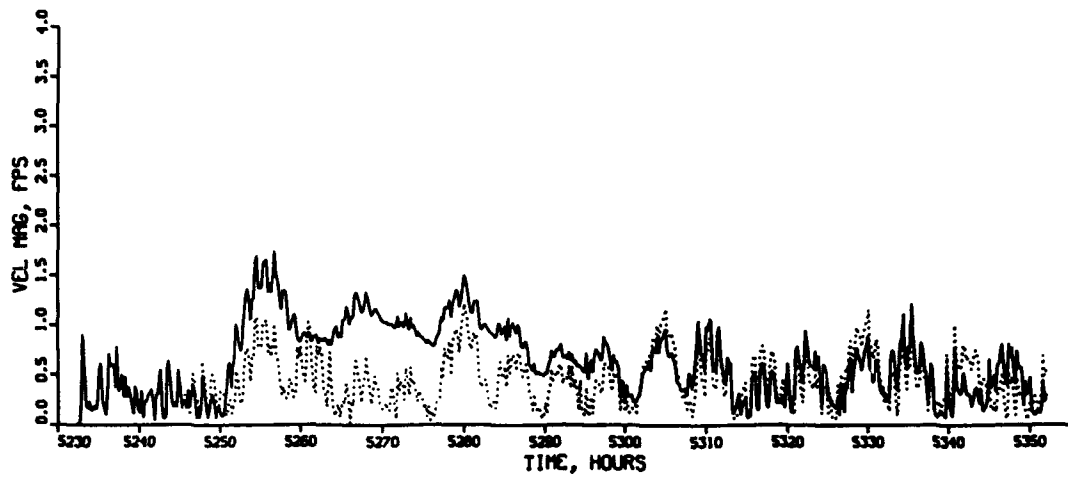


PAGE NO. 18 (25 ,22) LAYER NO. 2
— CASE 2 EXISTING

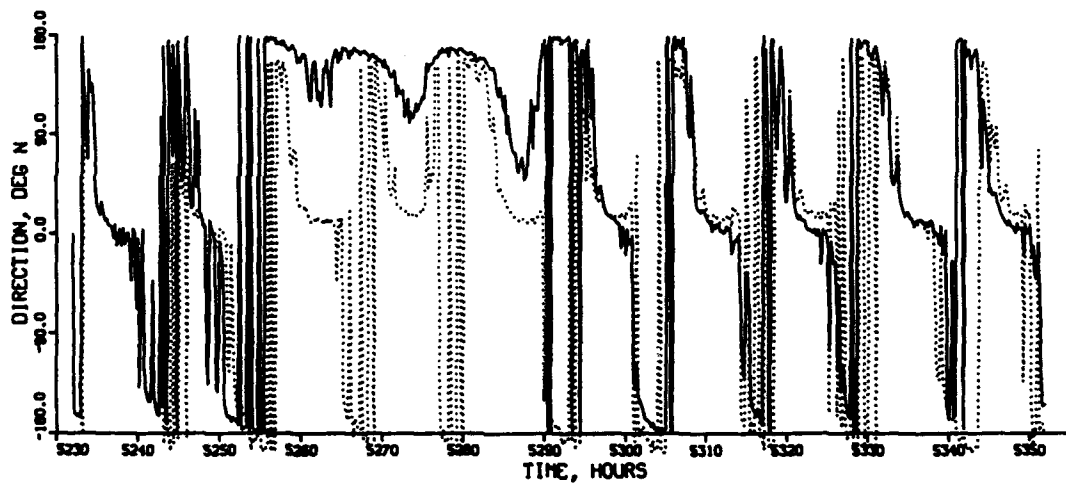
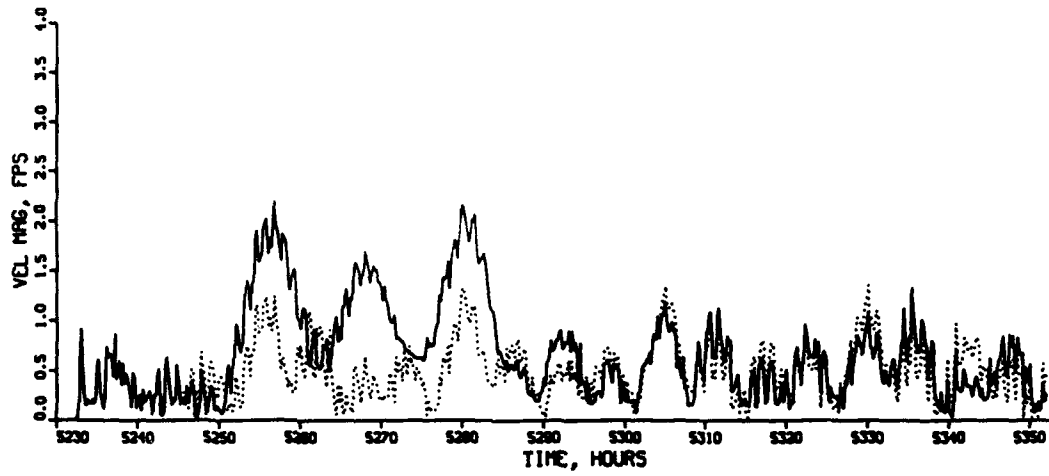


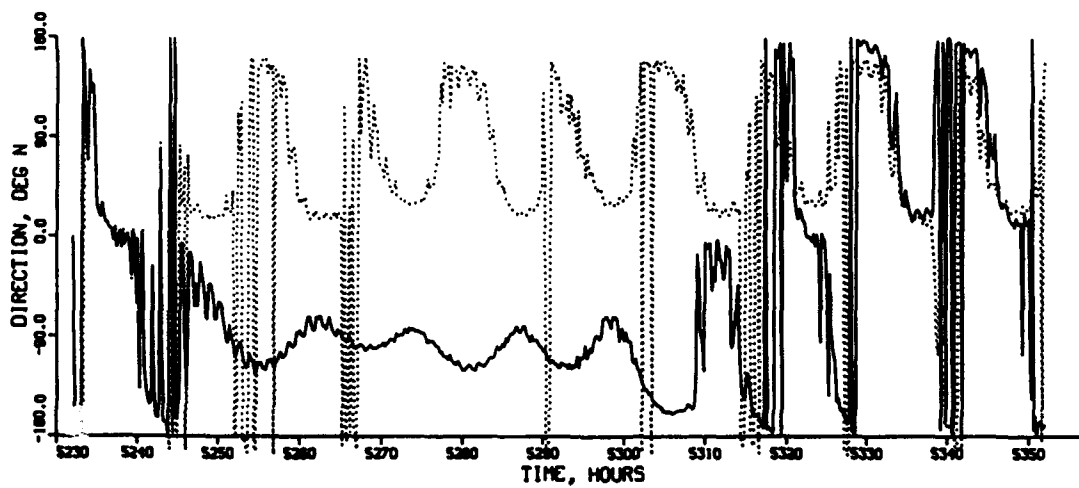
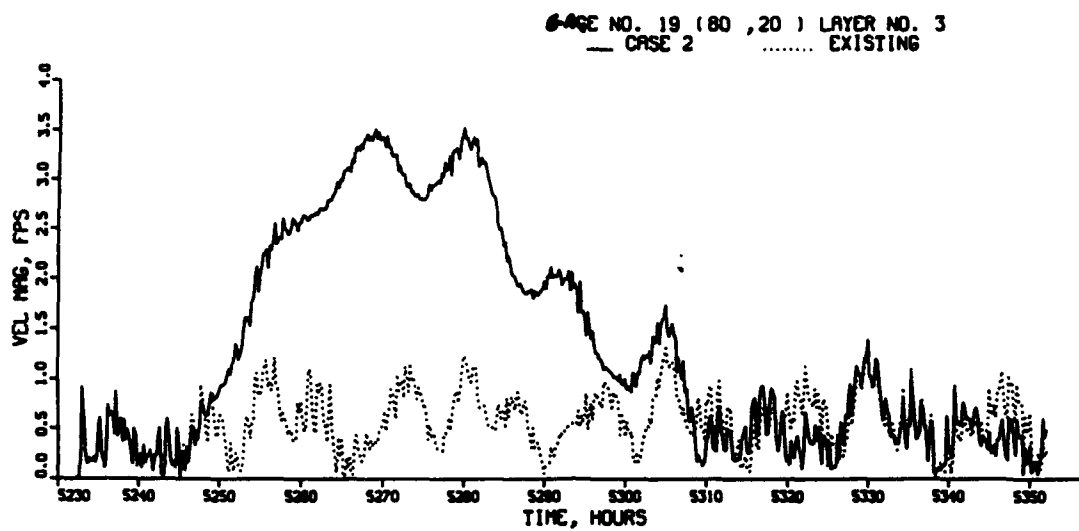


CASE NO. 19 (80, 20) LAYER NO. 1
— CASE 2 EXISTING



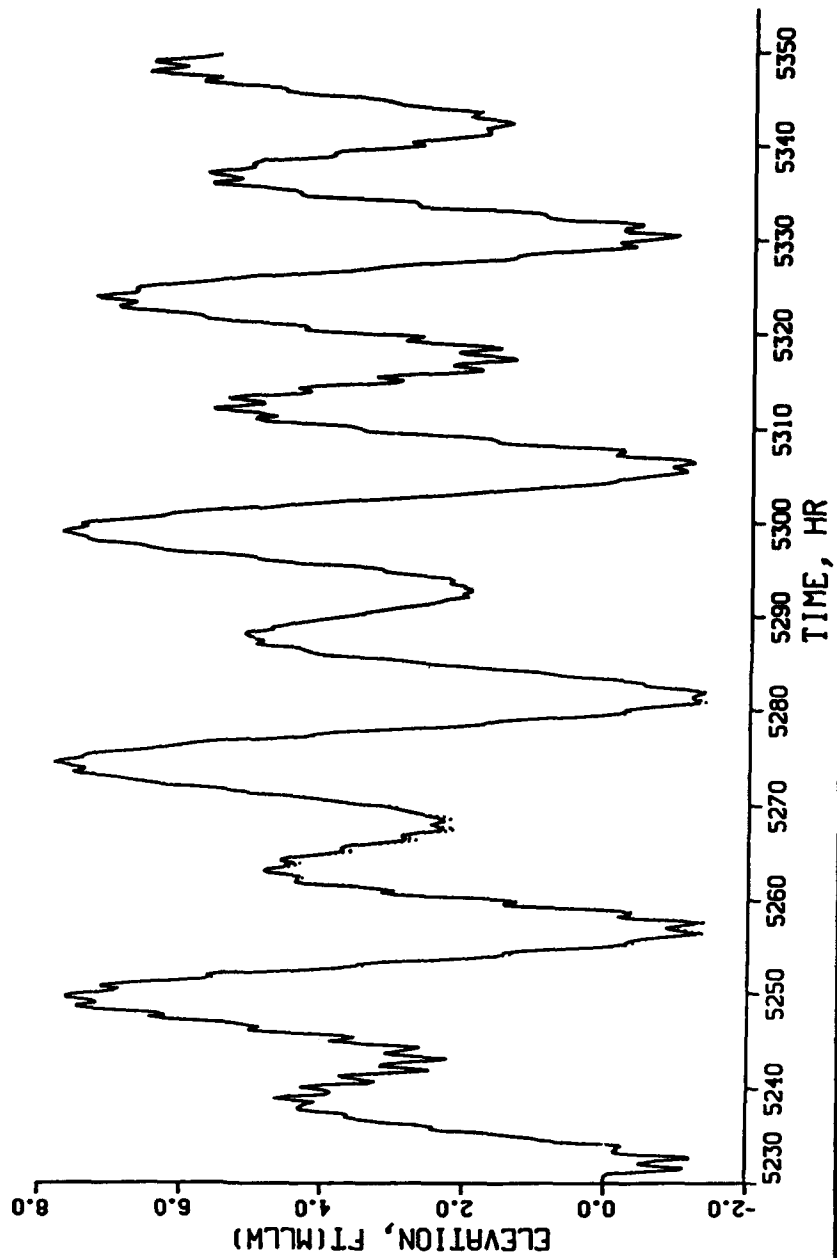
GAGE NO. 19 (80, 20) LAYER NO. 2
— CASE 2 EXISTING





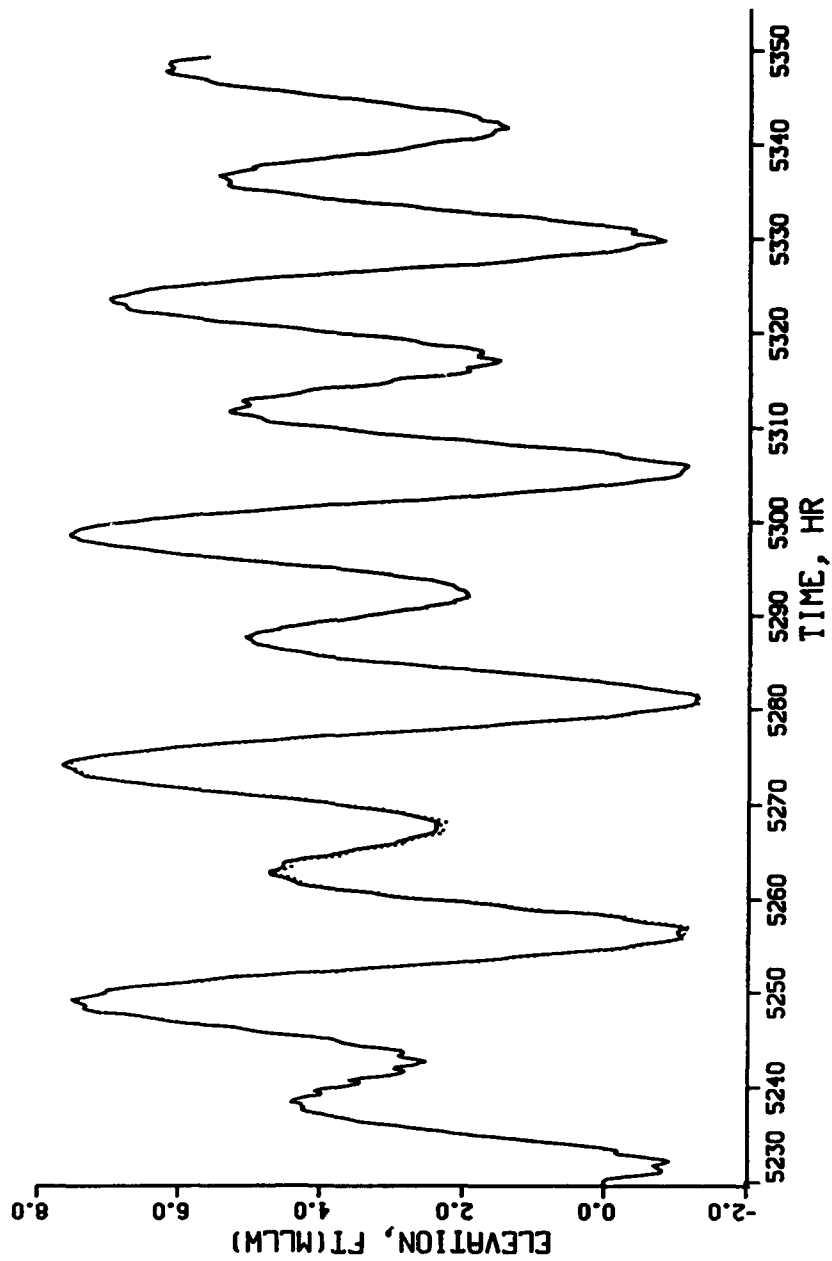
GAGE NO. 1 (46 , 80)

— CASE 2 EXISTING

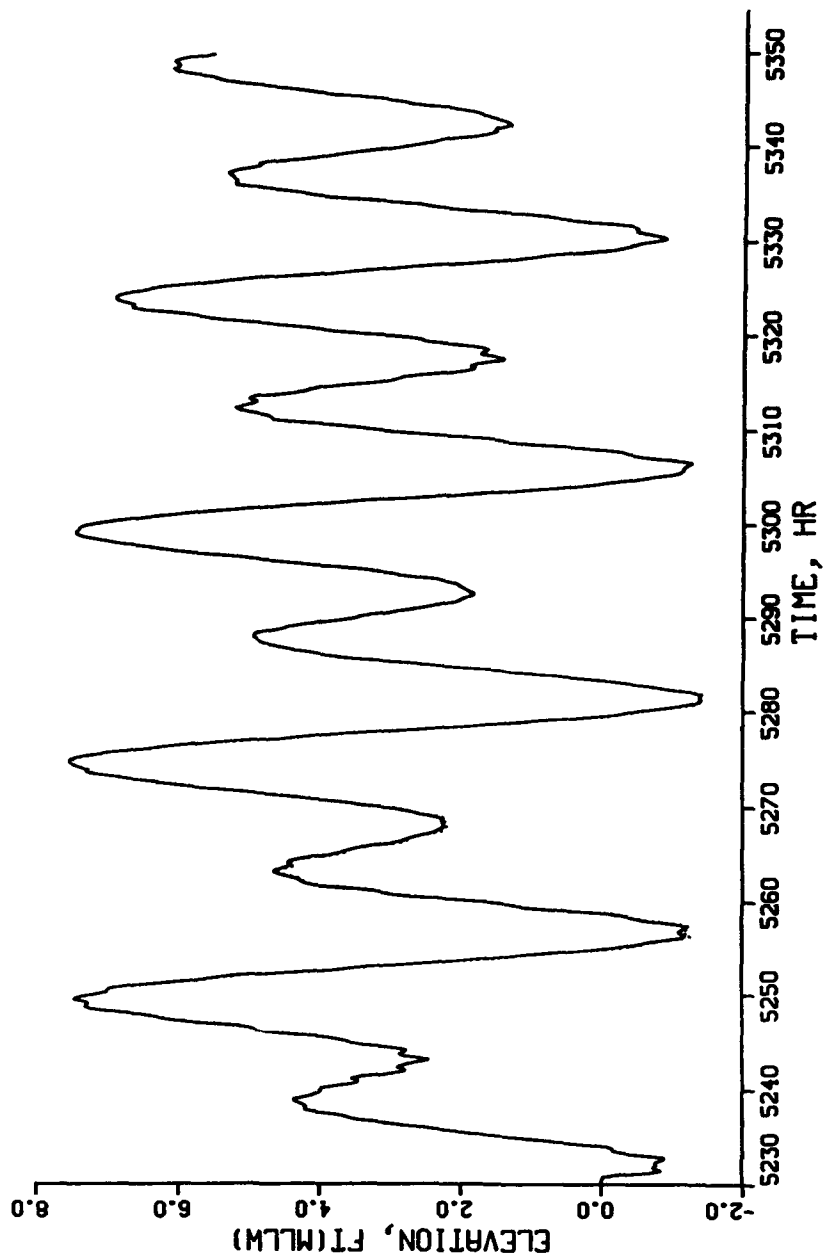


GAGE NO. 2 (15 , 42)

— CASE 2 EXISTING

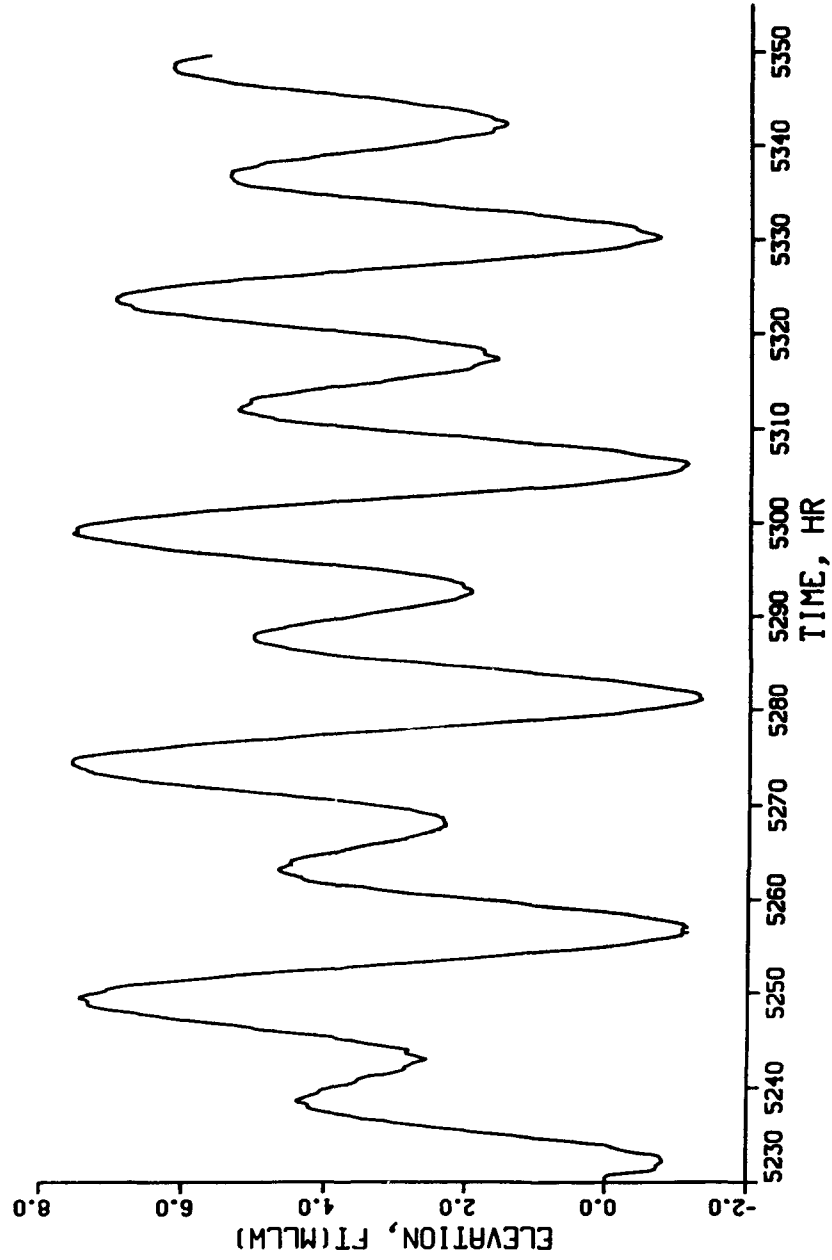


GAGE NO. 3 (55 , 50)
— CASE 2 EXISTING



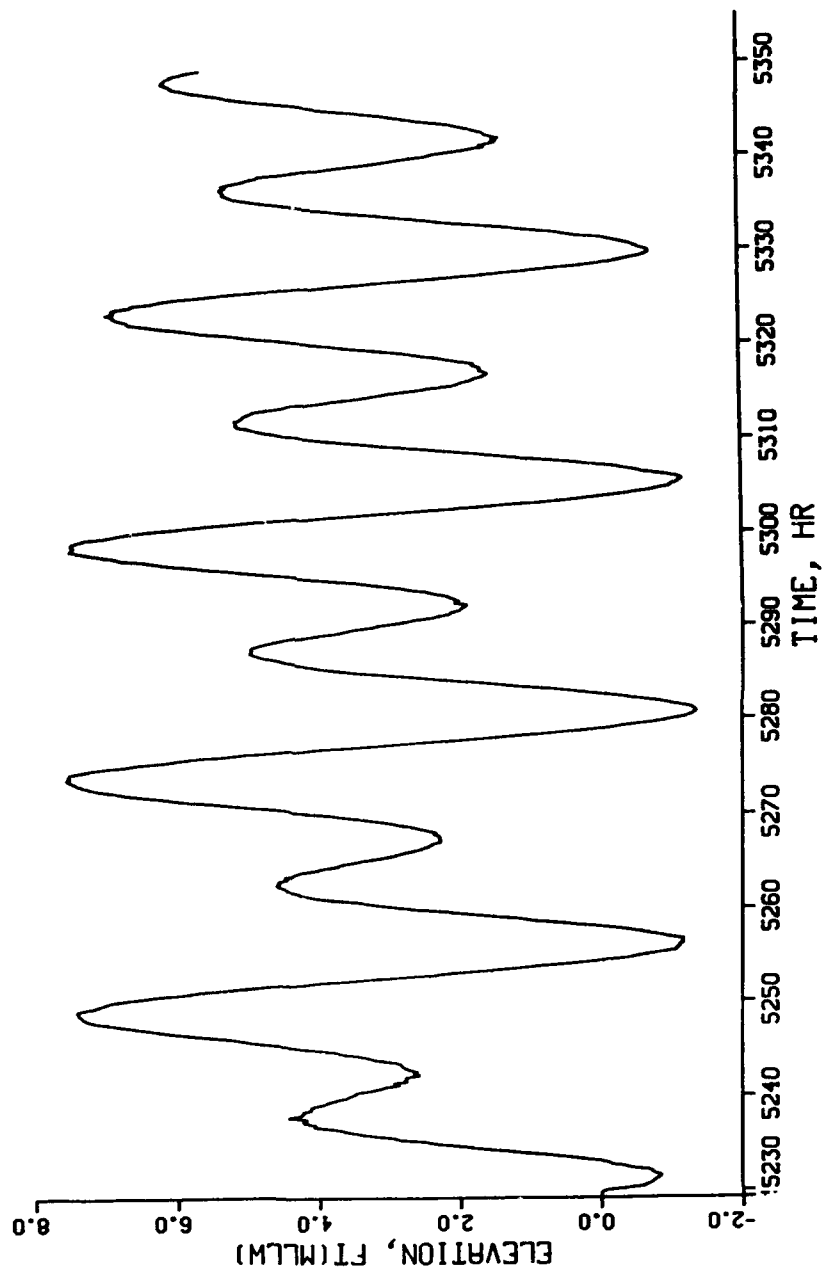
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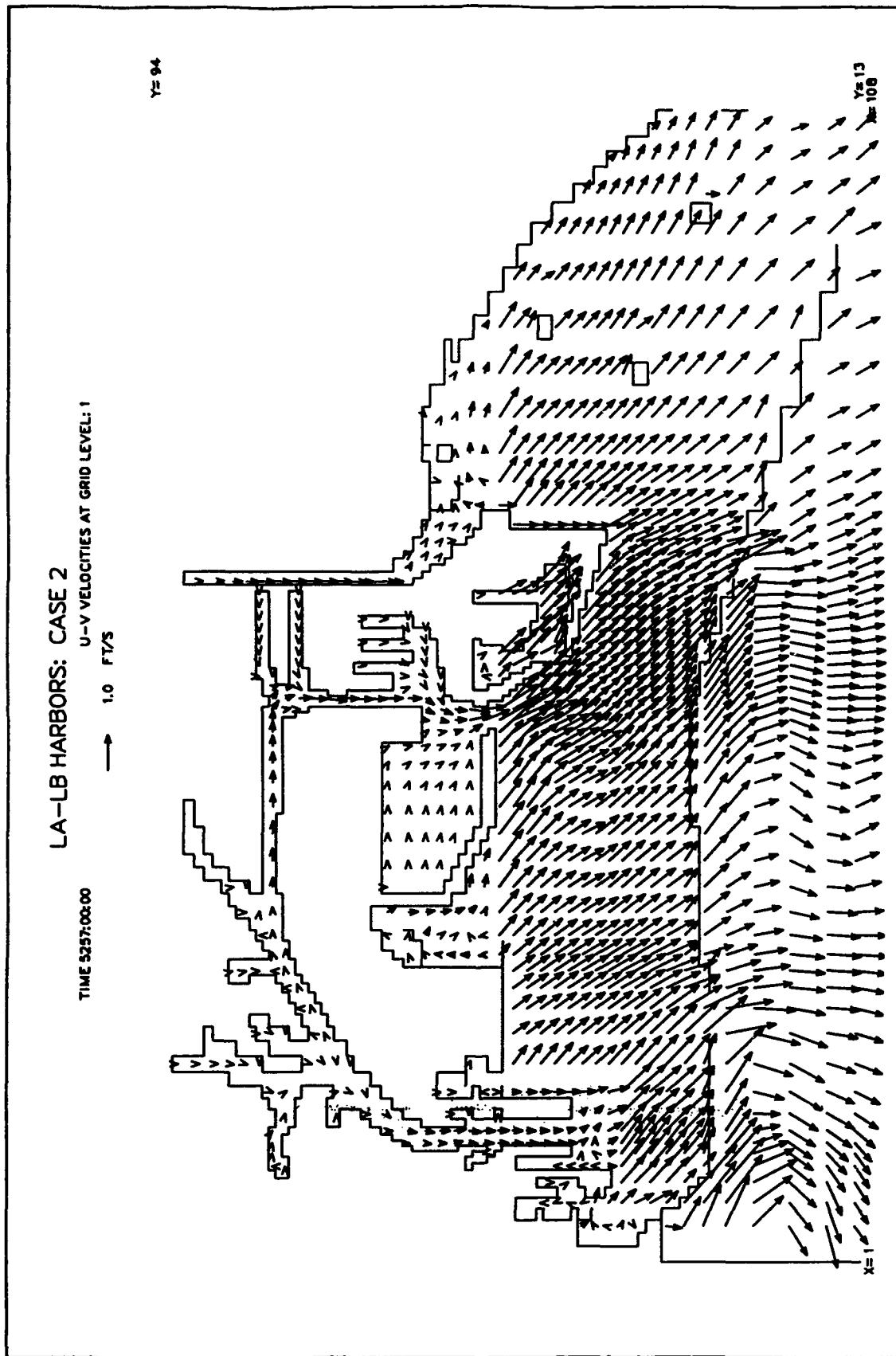
— CASE 2 EXISTING



GAGE NO. 5 (101 , 17)

— CASE 2 EXISTING





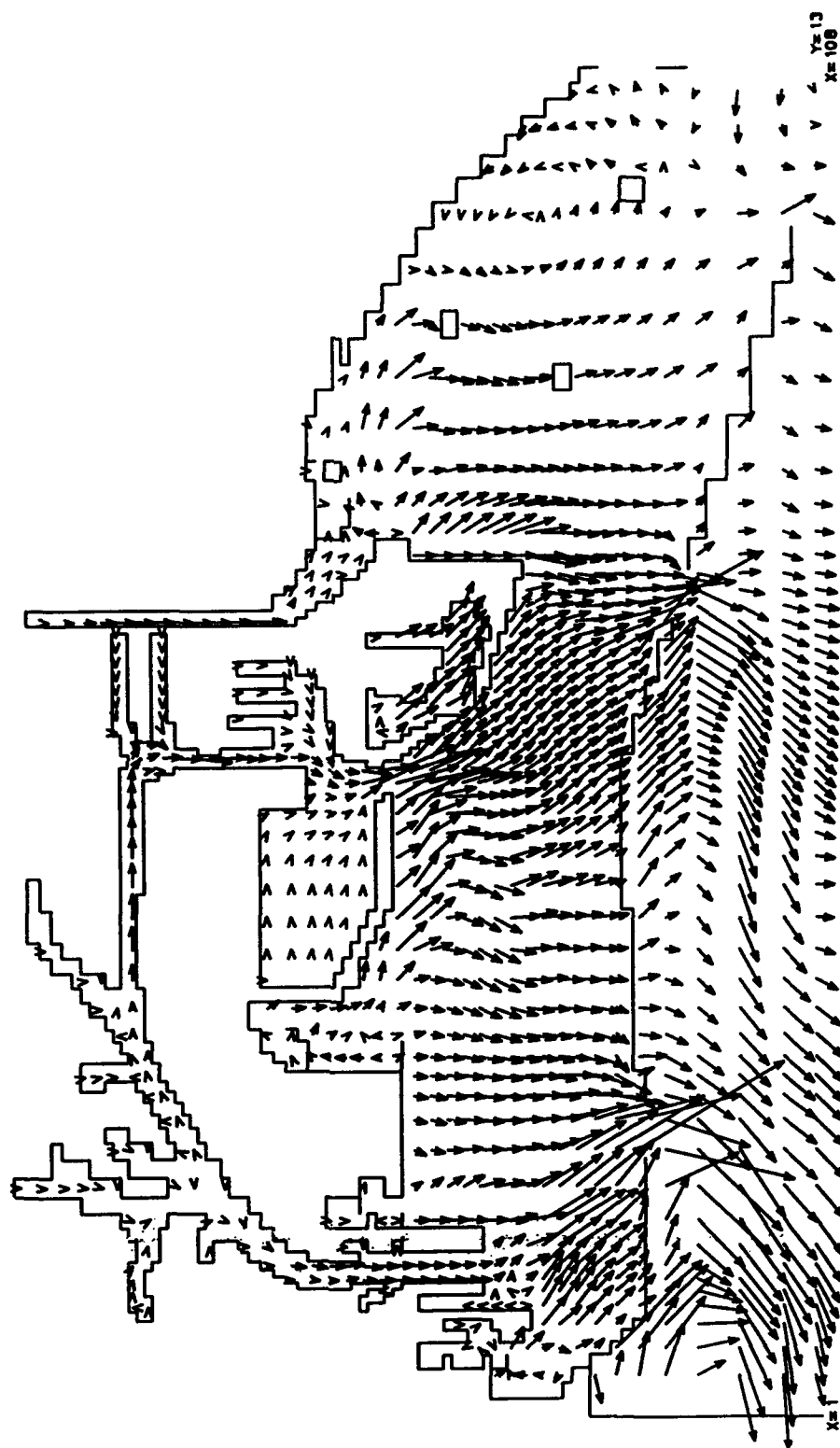
LA-LB HARBORS: CASE 2

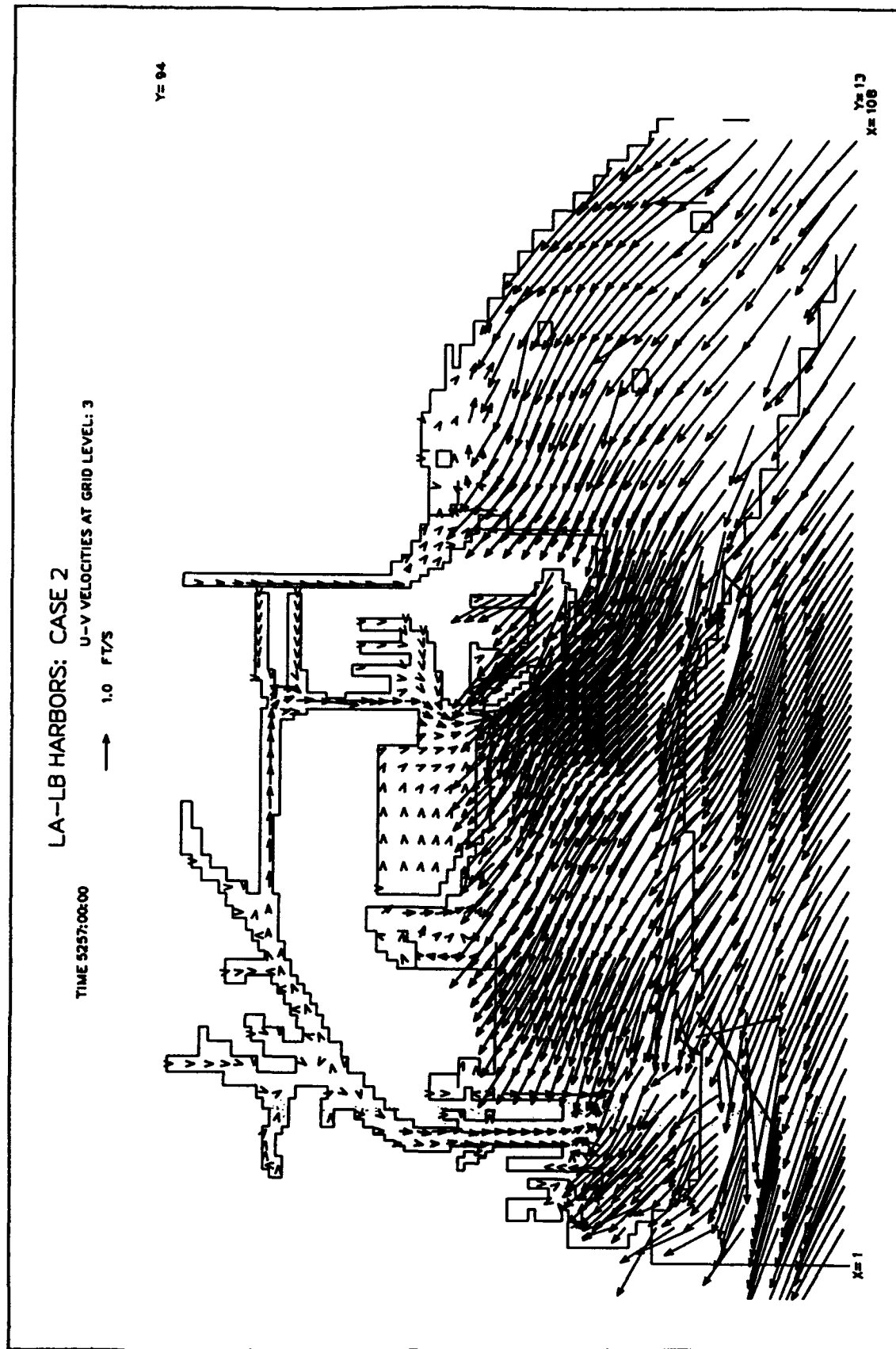
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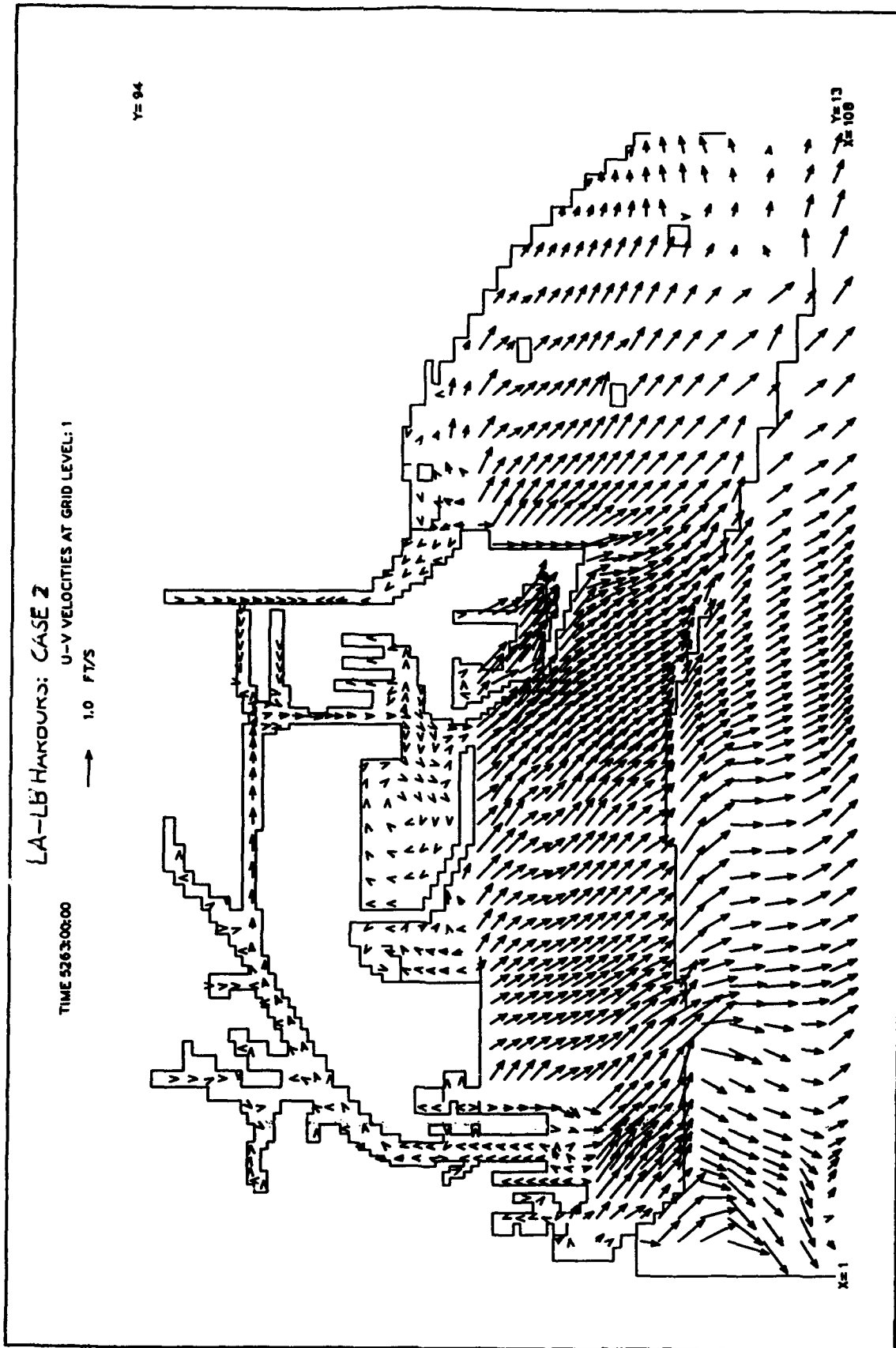
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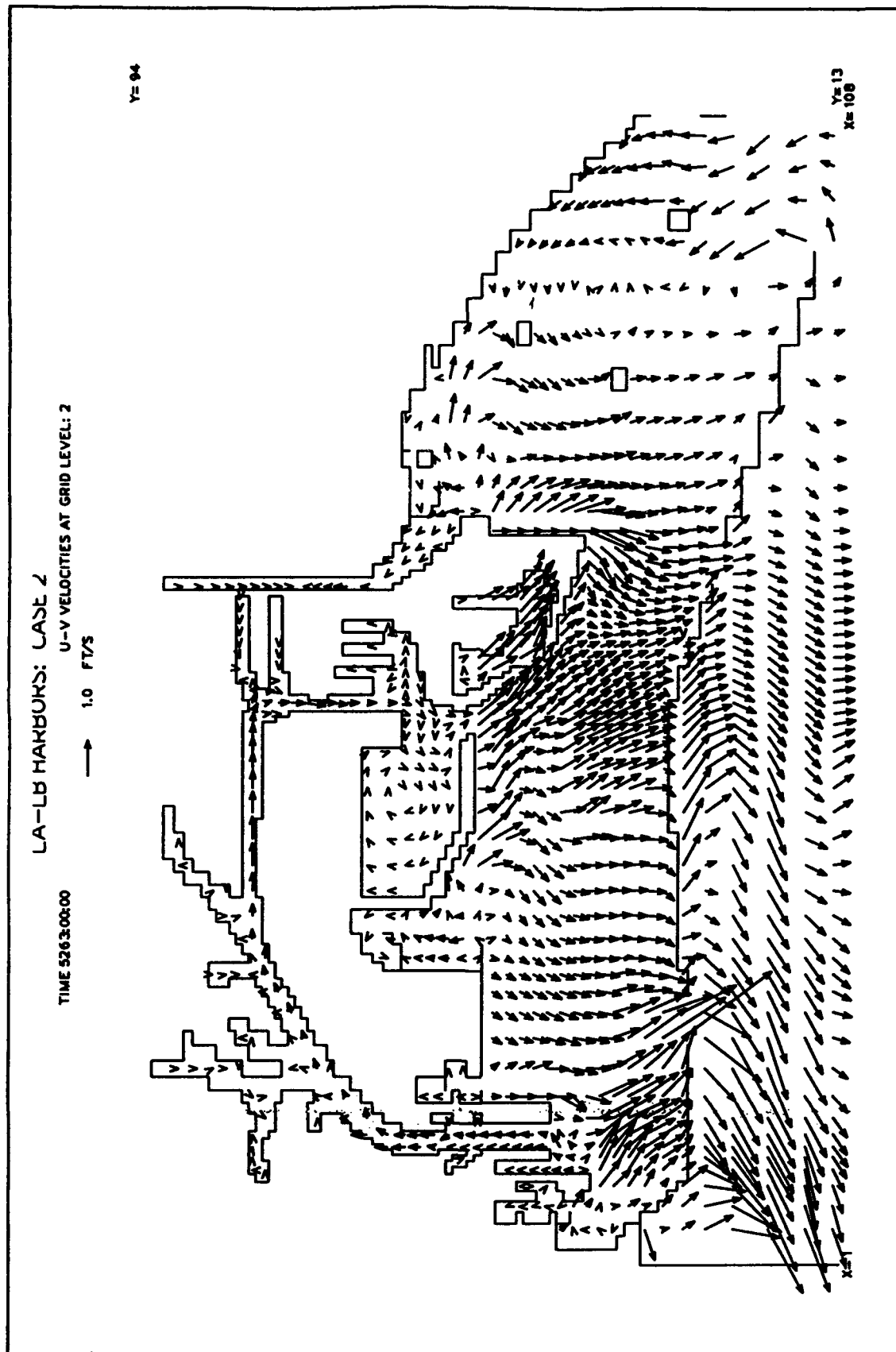
→ 1.0 FT/S

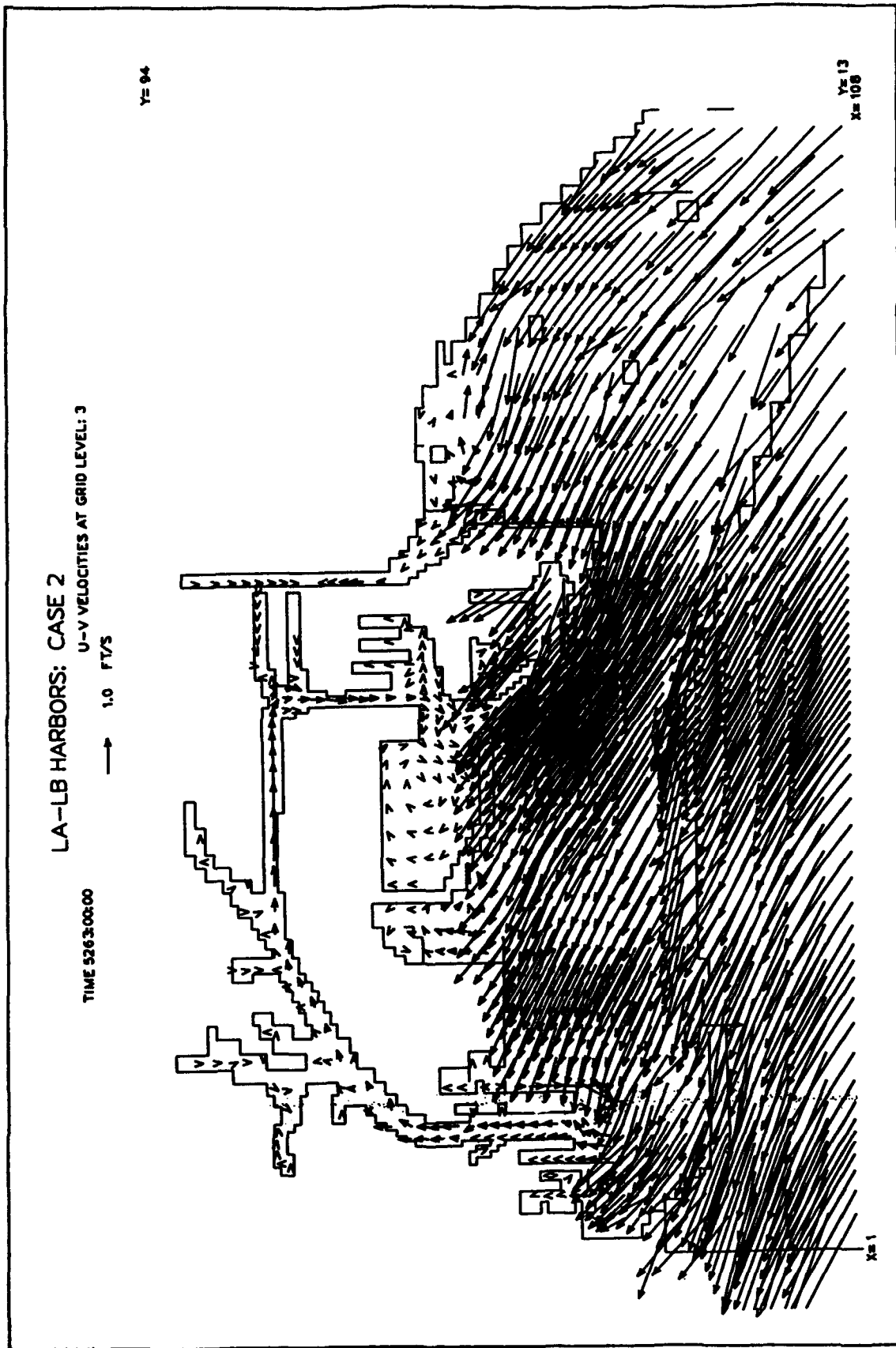
Y= 94

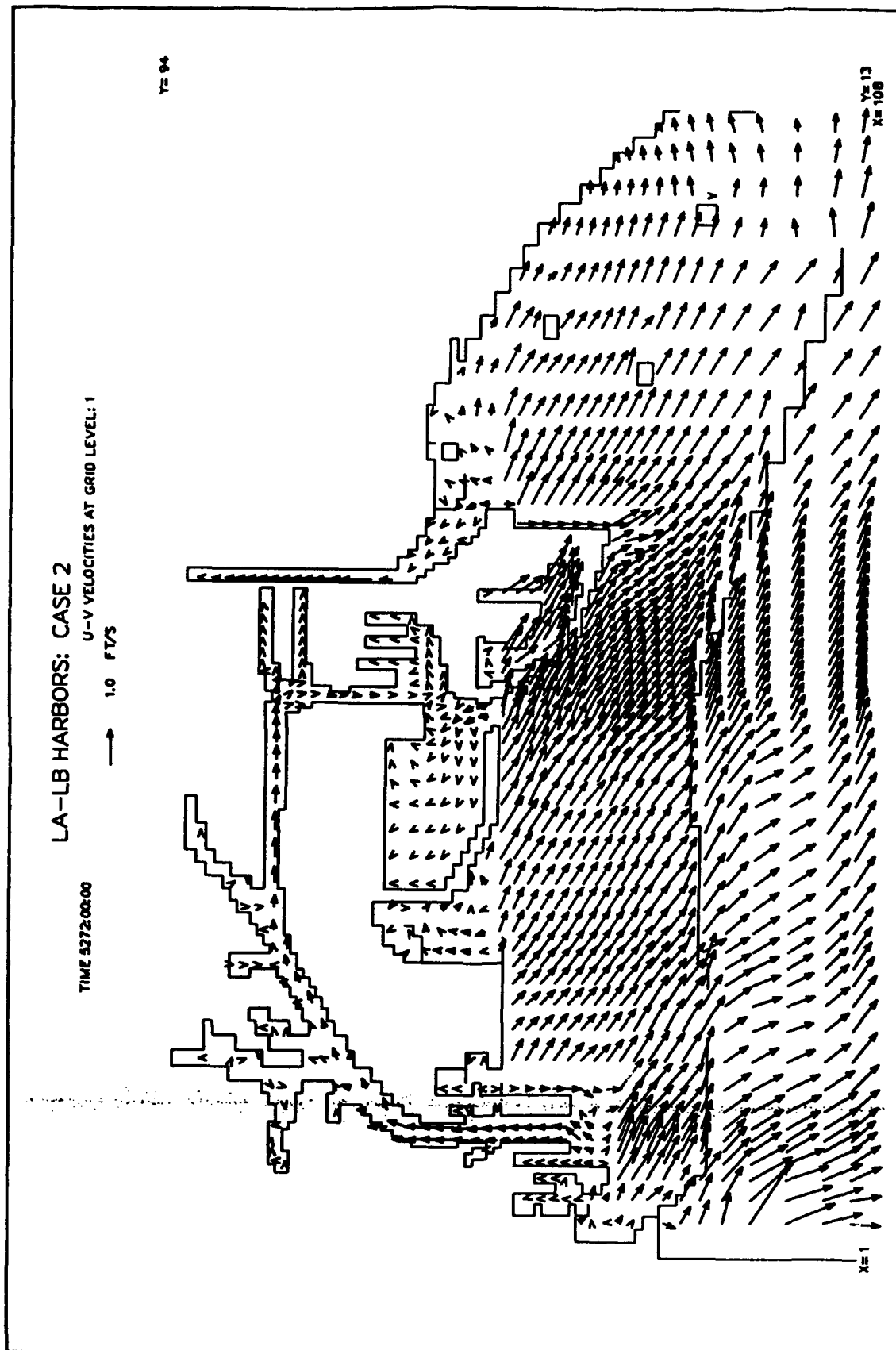


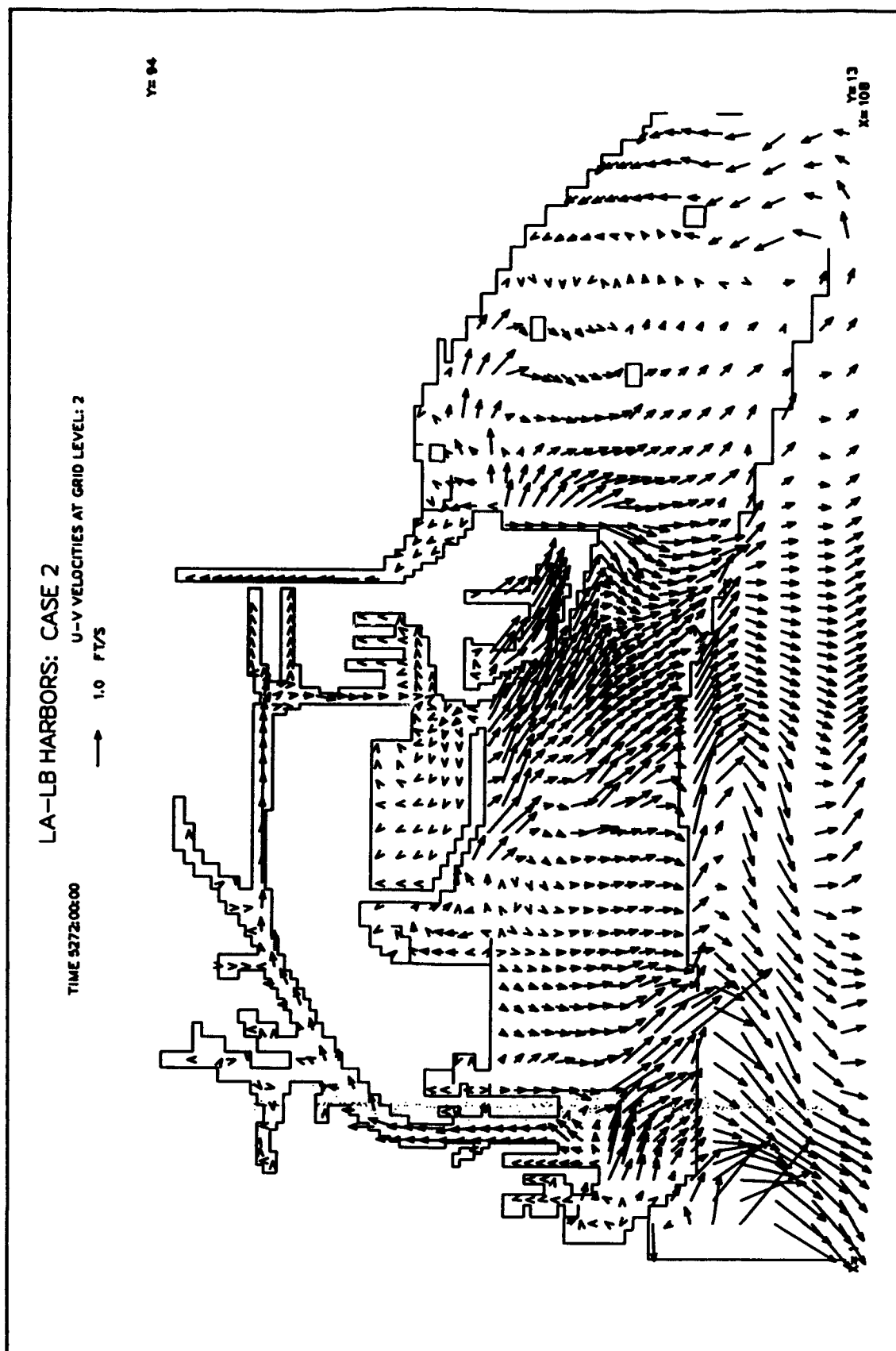


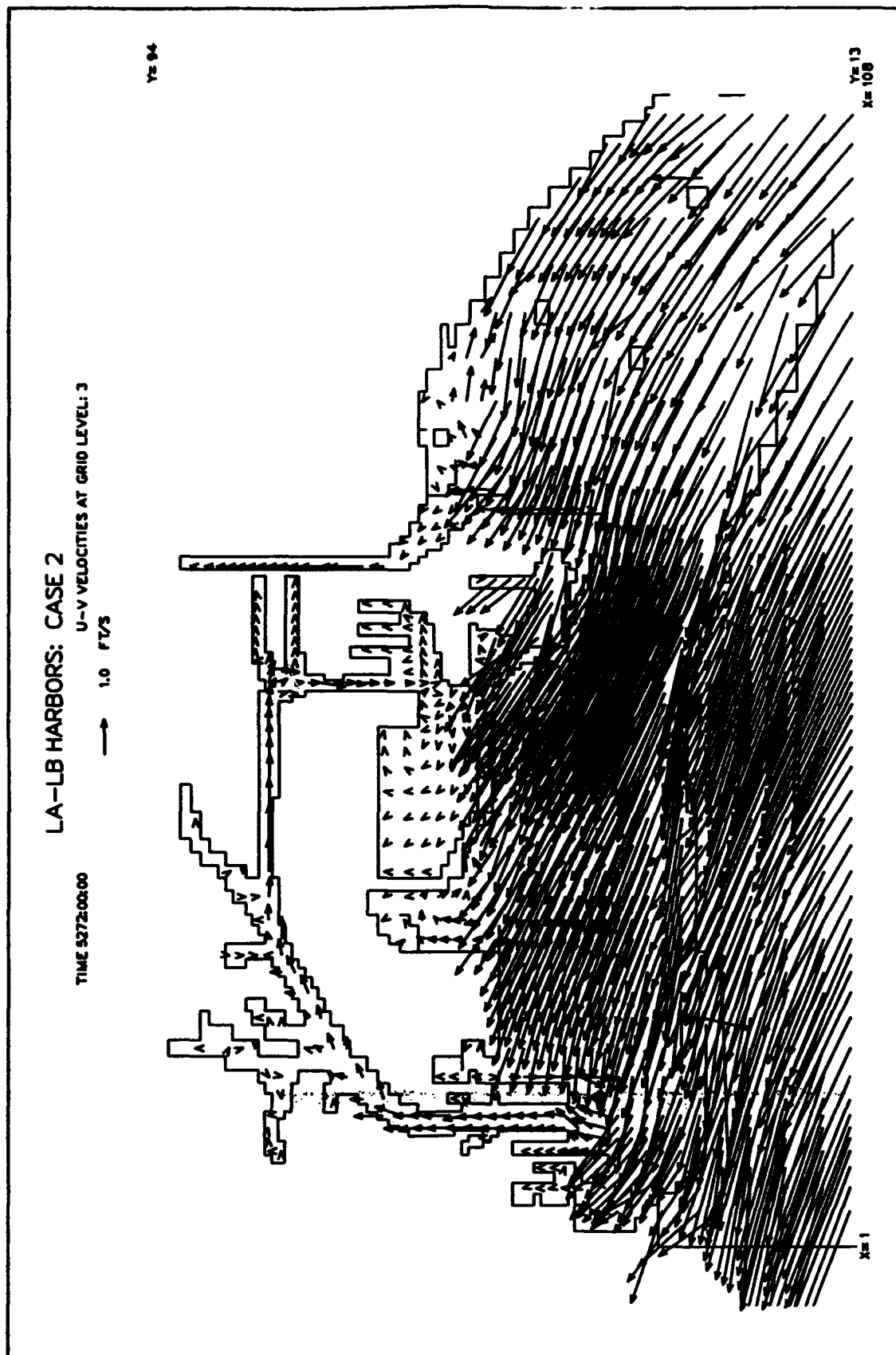


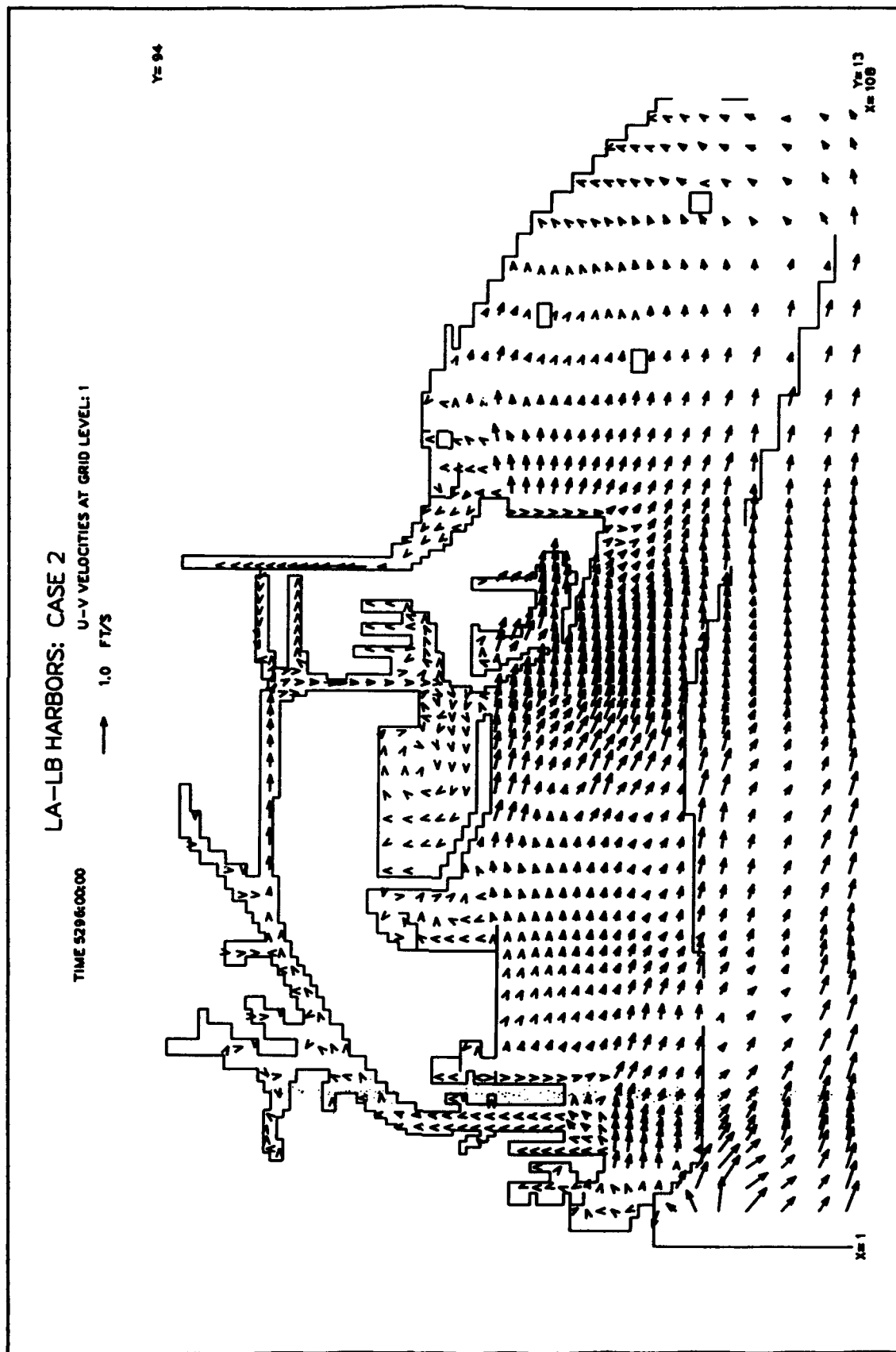


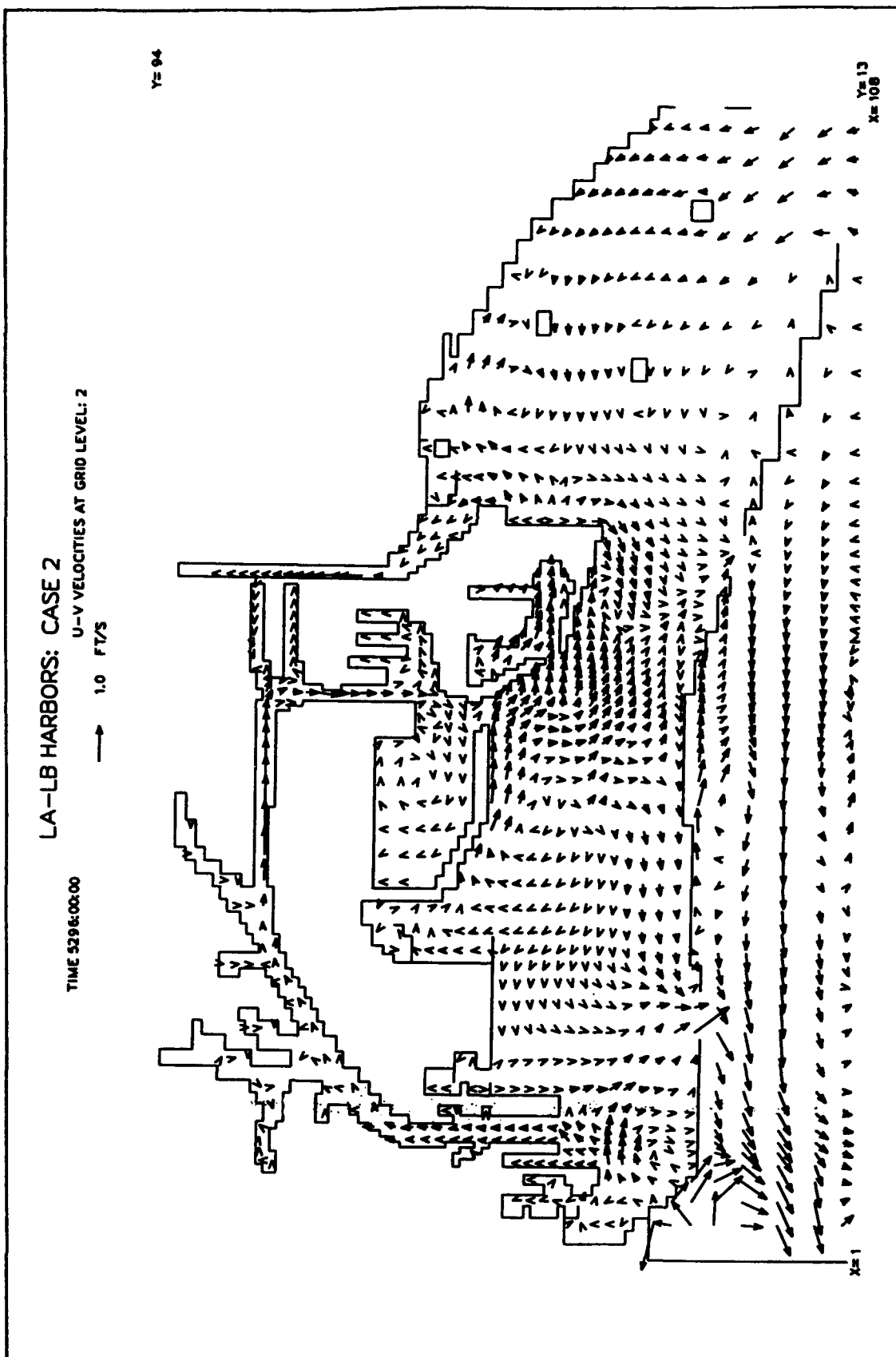


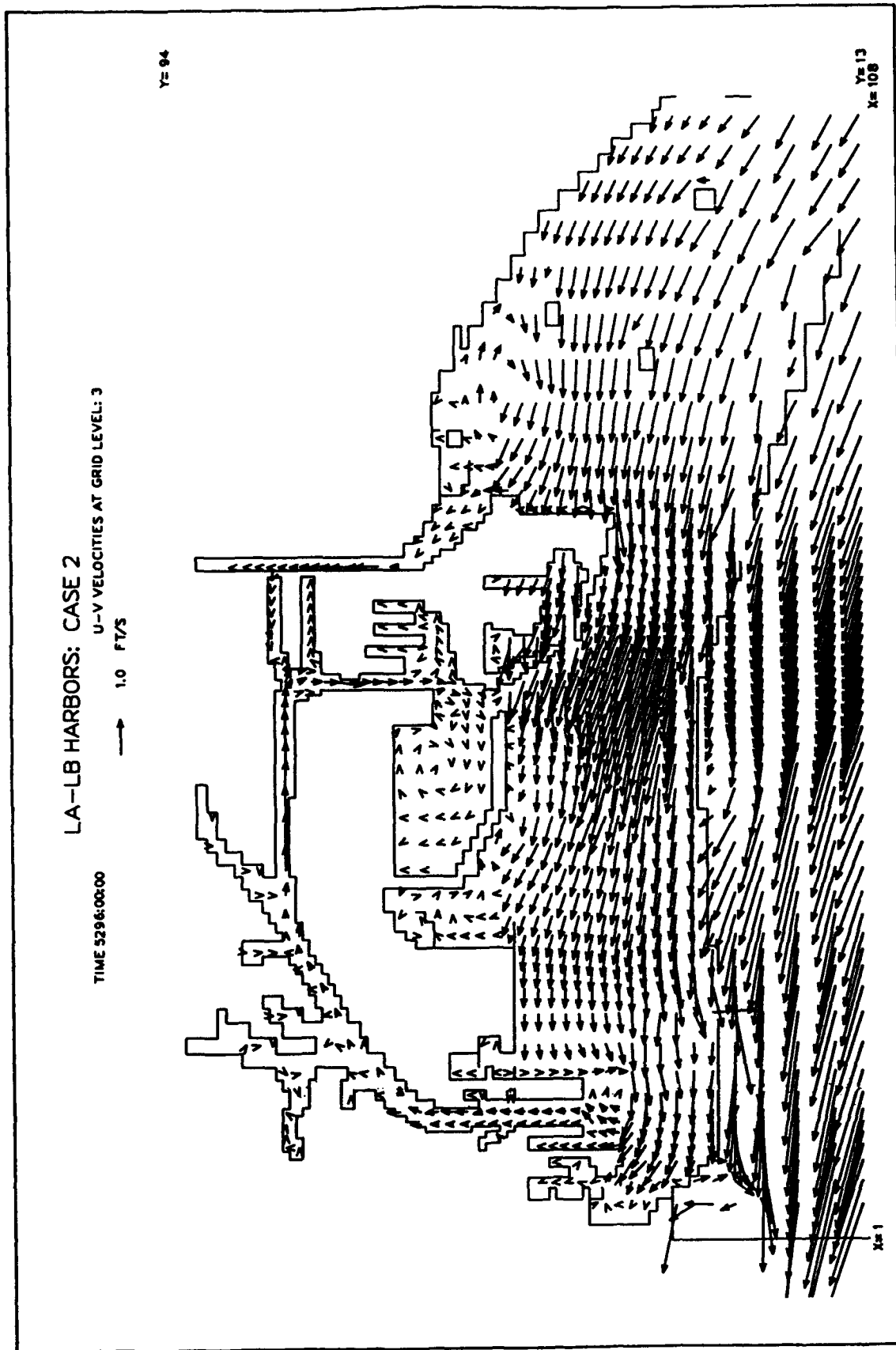


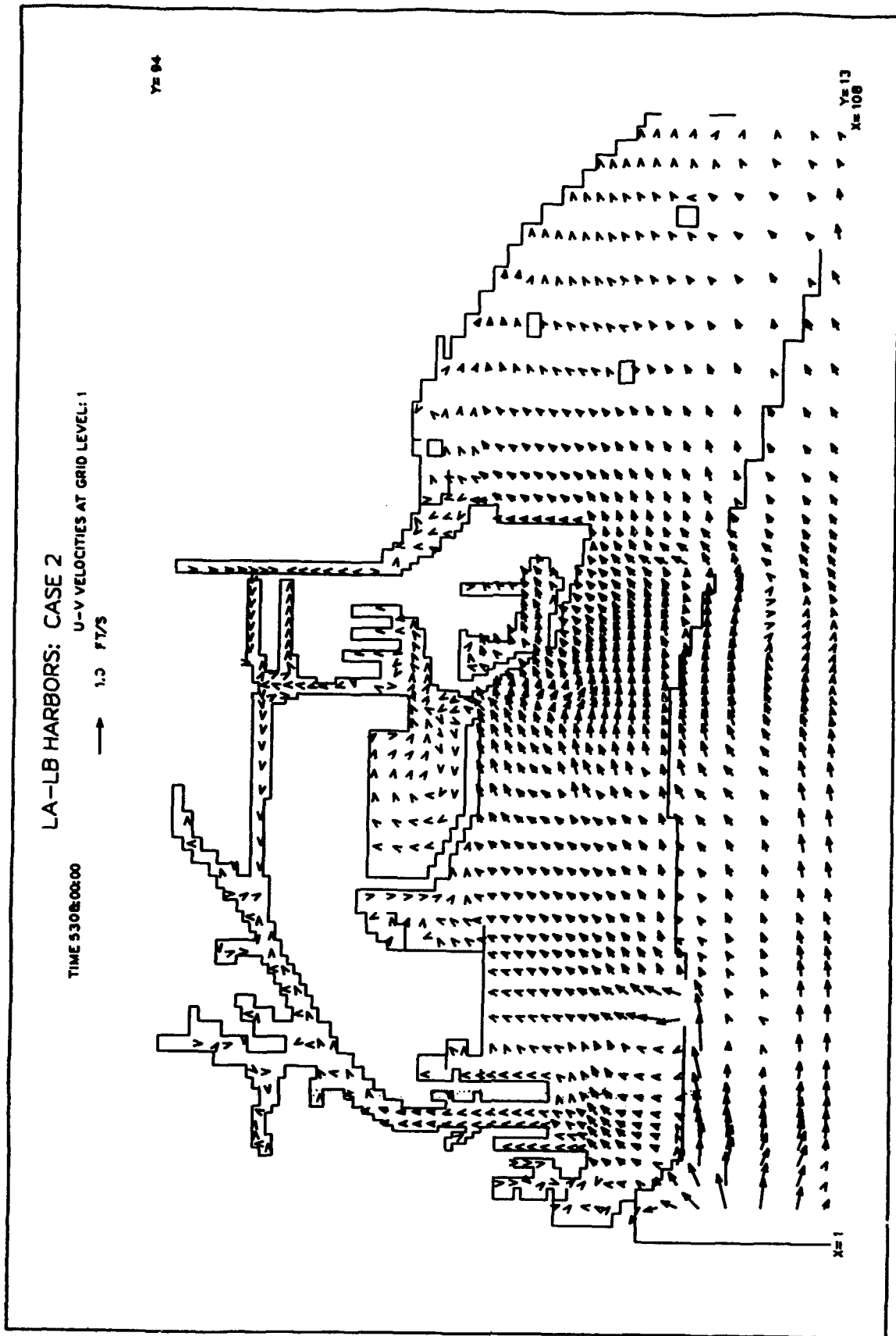












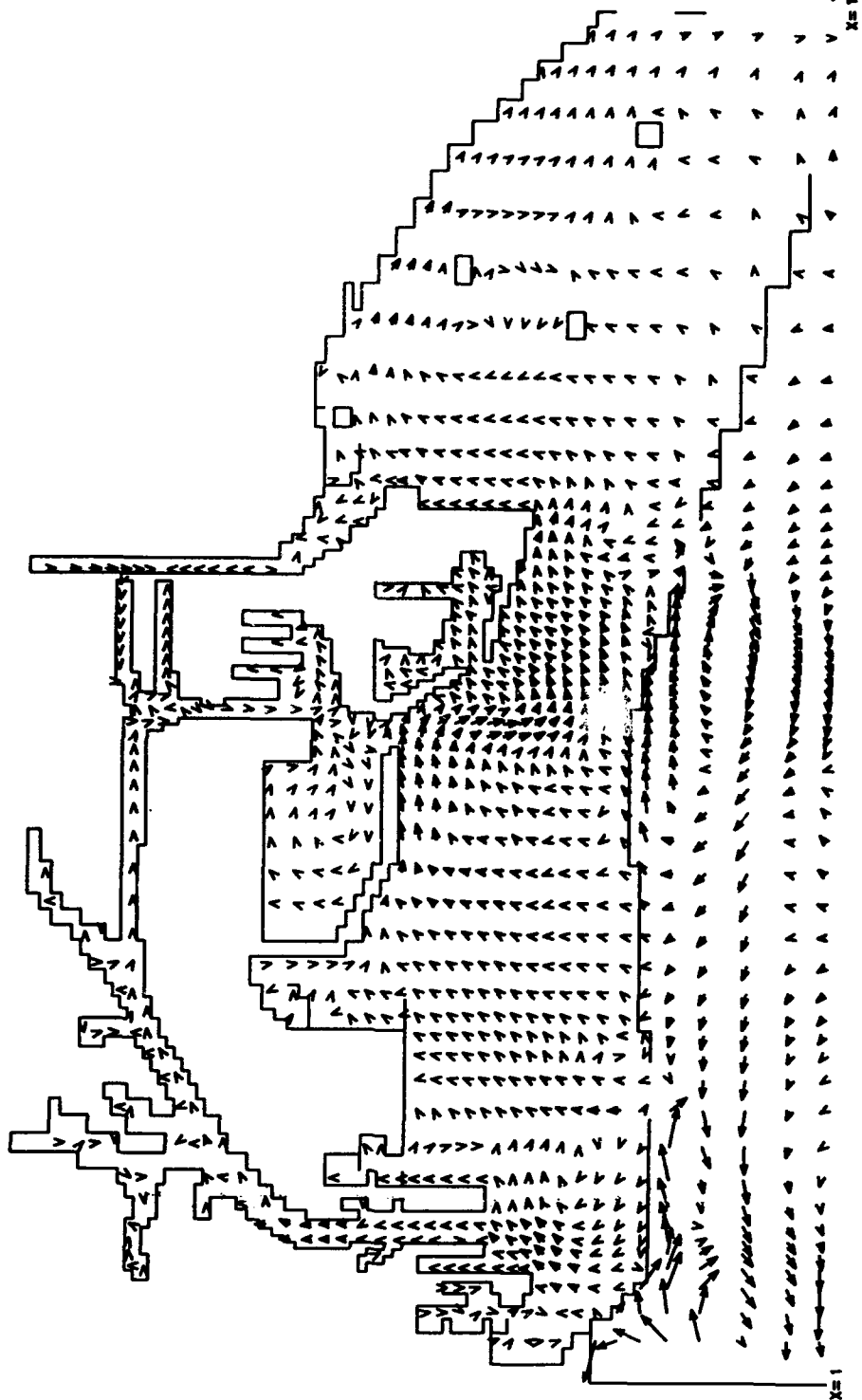
LA-LB HARBORS: CASE 2

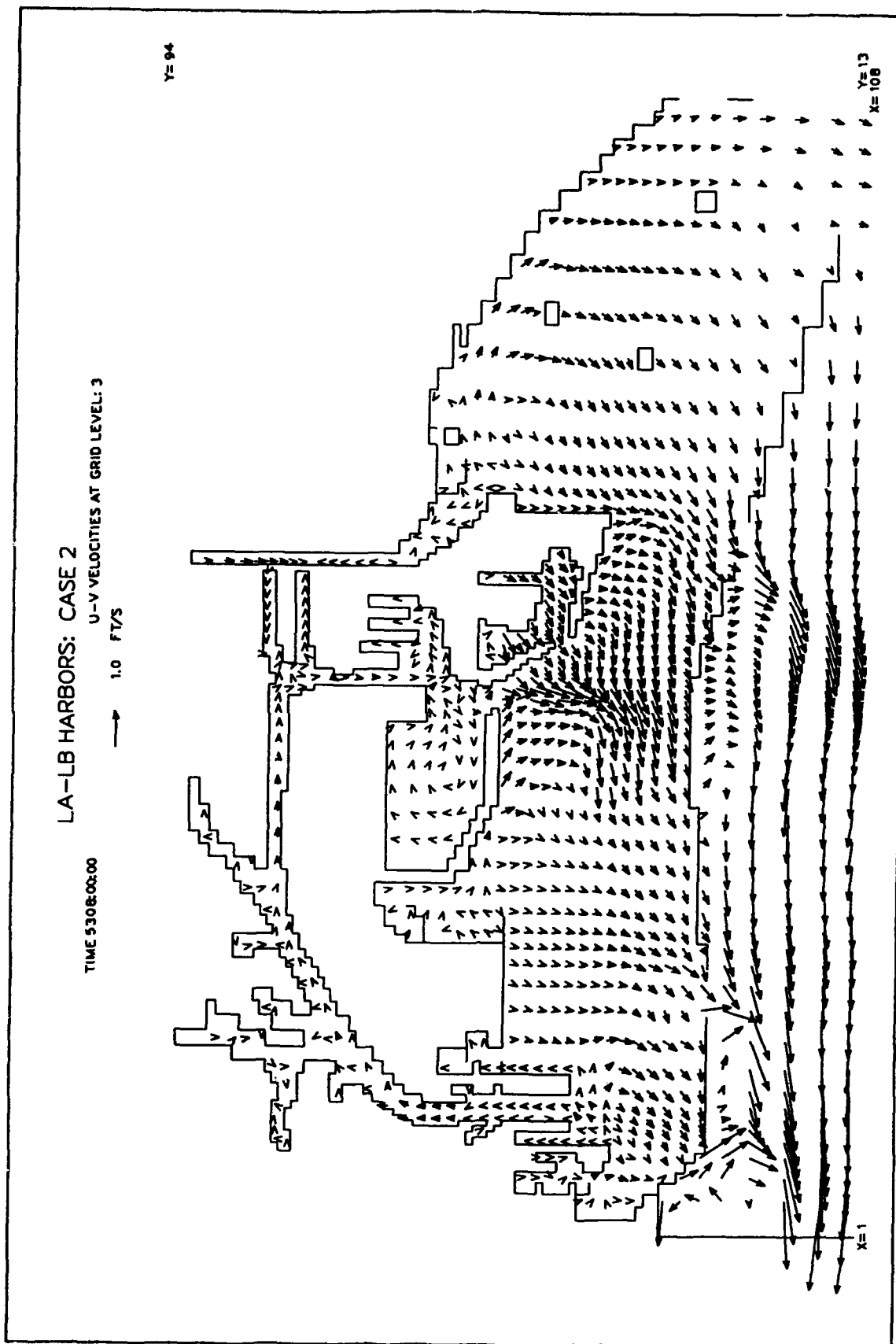
TIME 930&00:00

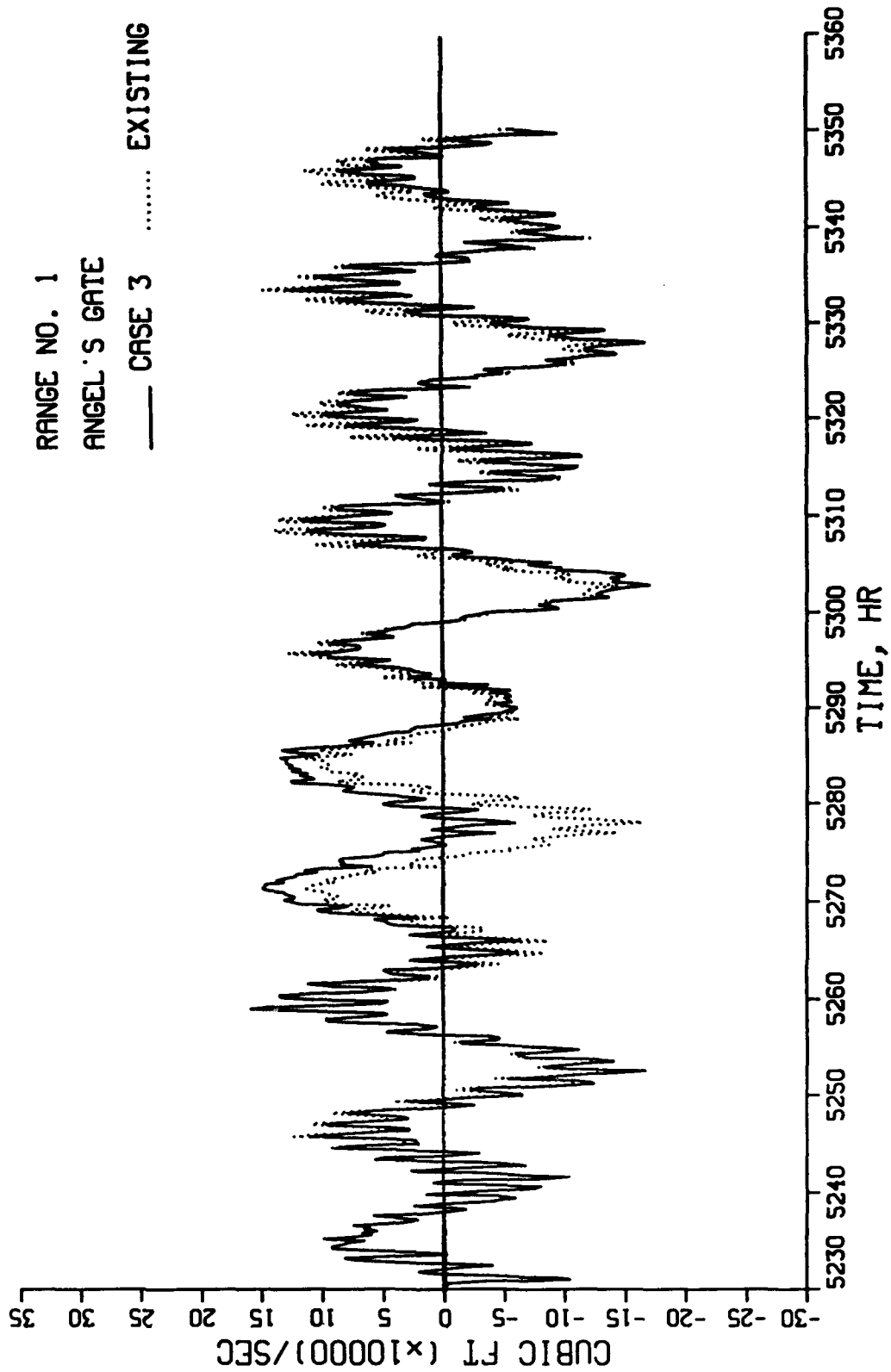
U-V VELOCITIES AT GRID LEVEL: 2

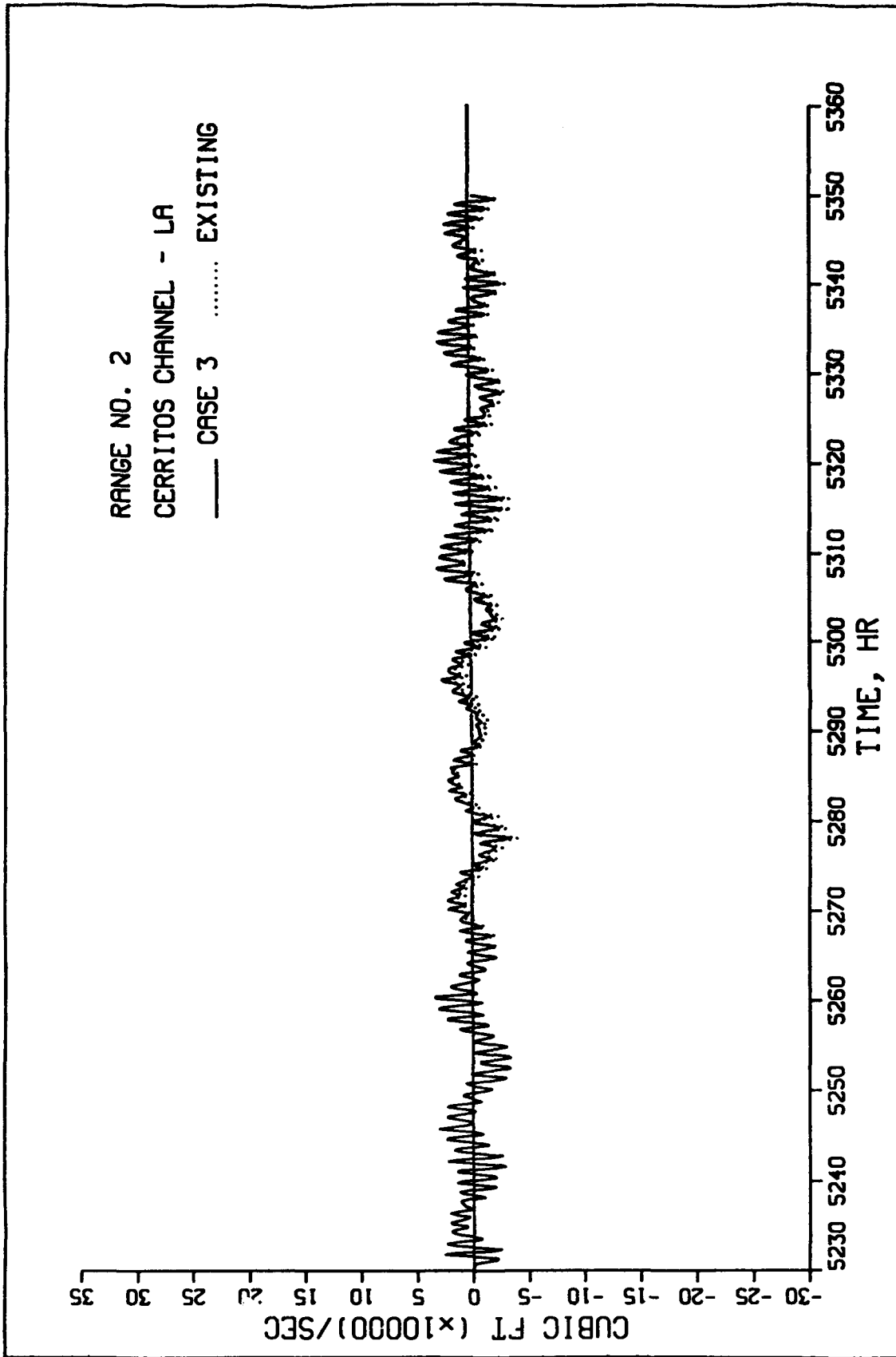
→ 1.0 FT/S

Y= 94

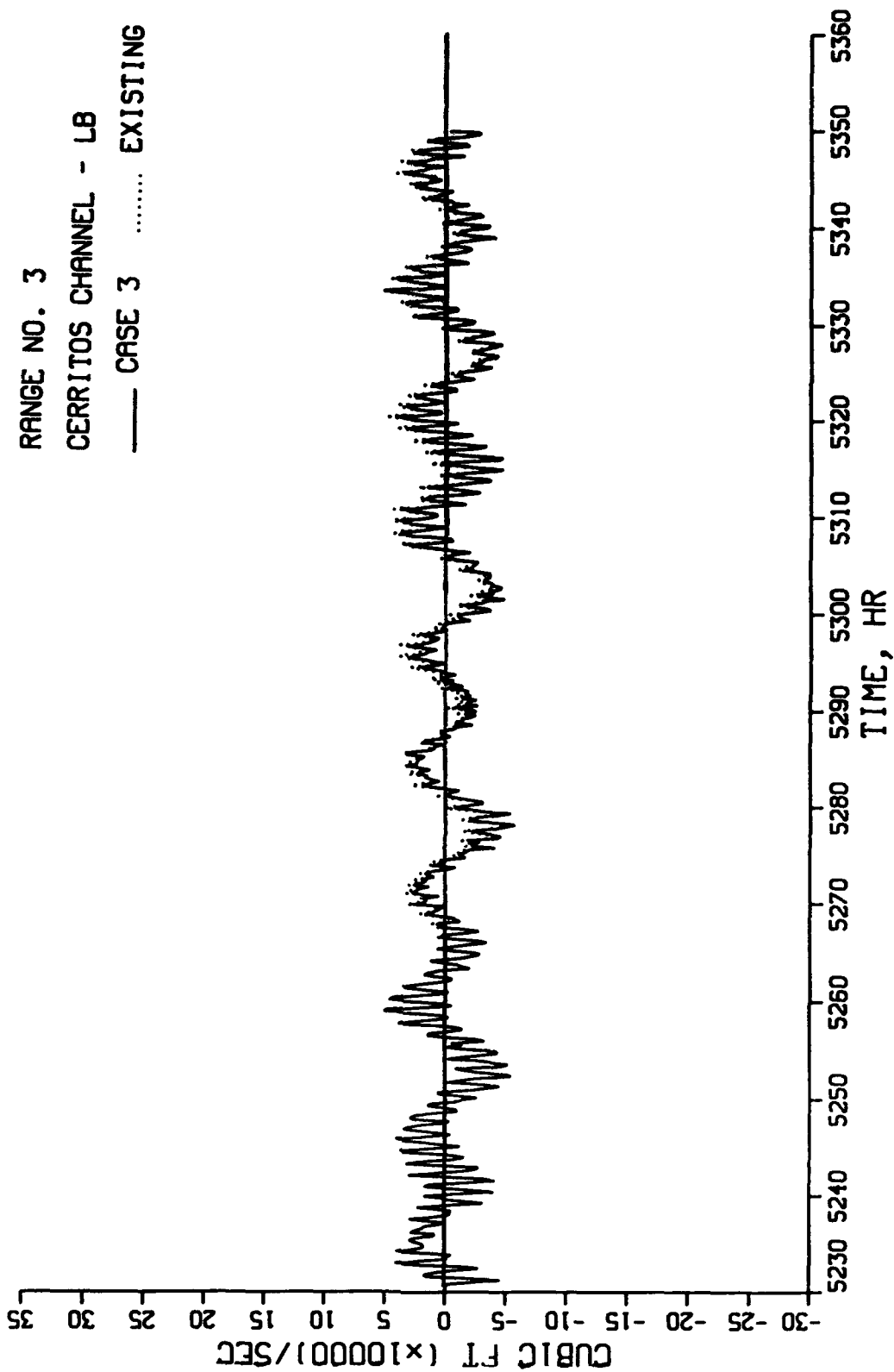




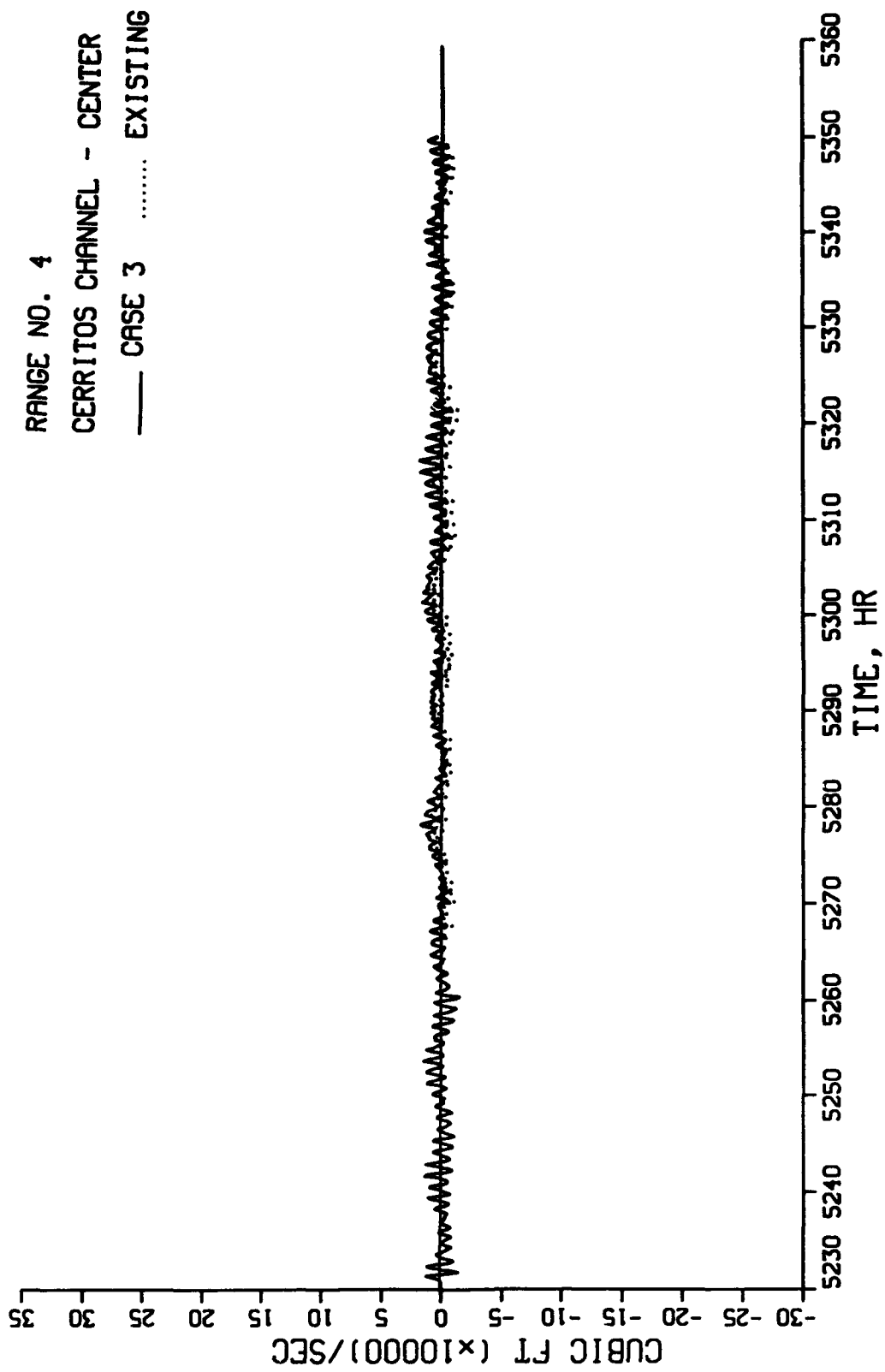




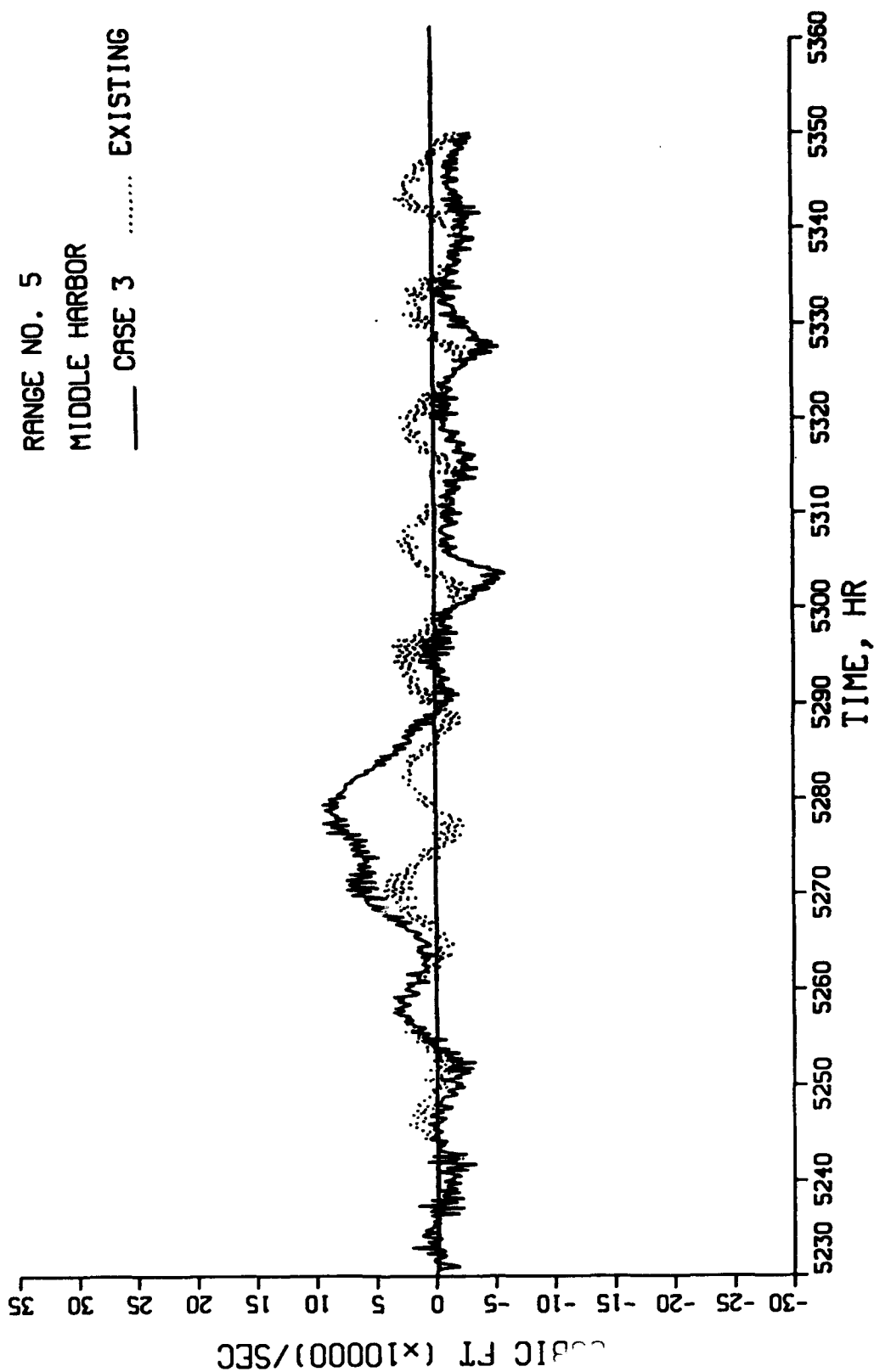
RANGE NO. 3
CERRITOS CHANNEL - LB
— CASE 3 EXISTING



RANGE NO. 4
 CERRITOS CHANNEL - CENTER
 — CASE 3 EXISTING



RANGE NO. 5
MIDDLE HARBOR
— CASE 3 EXISTING



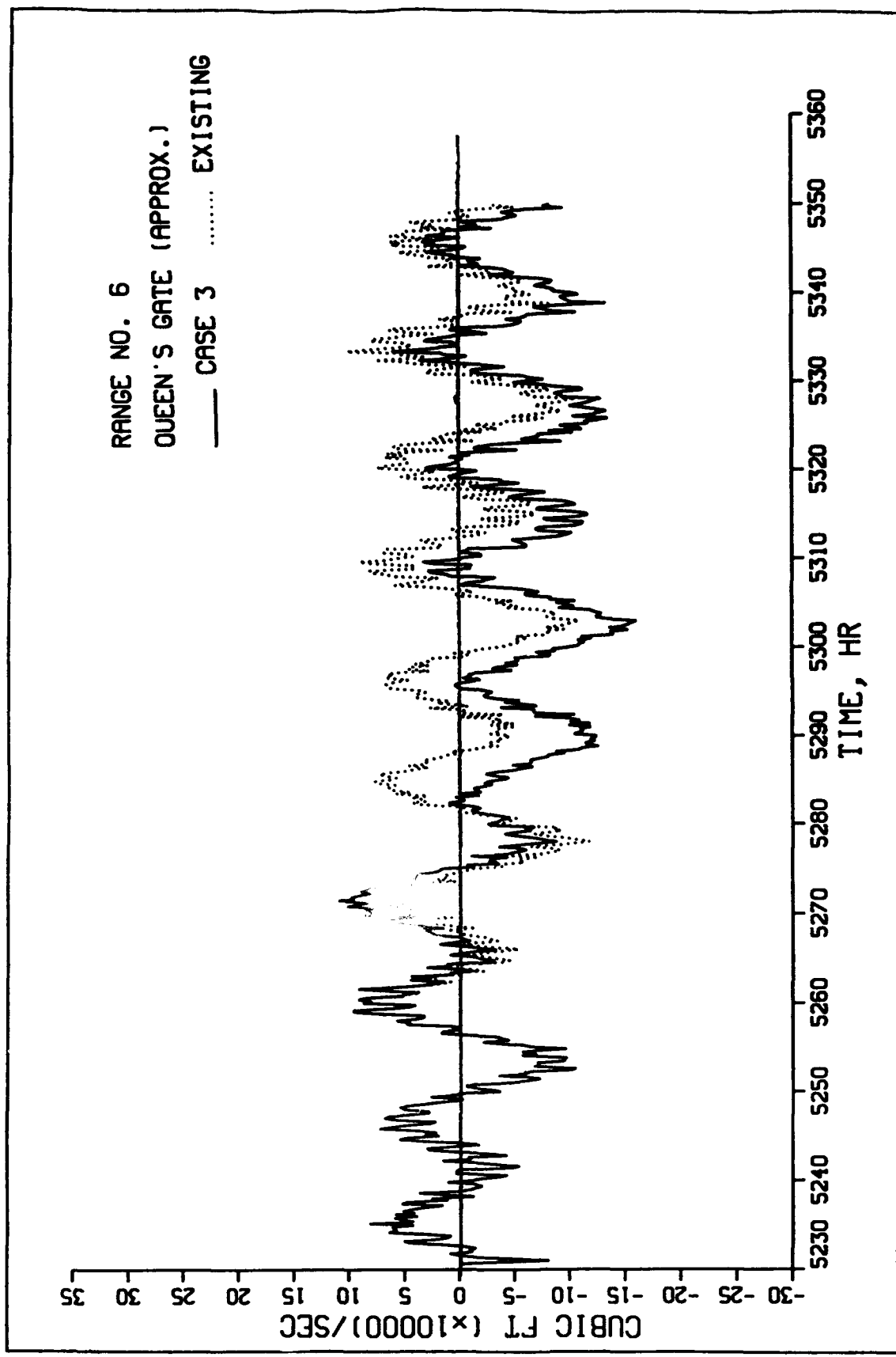
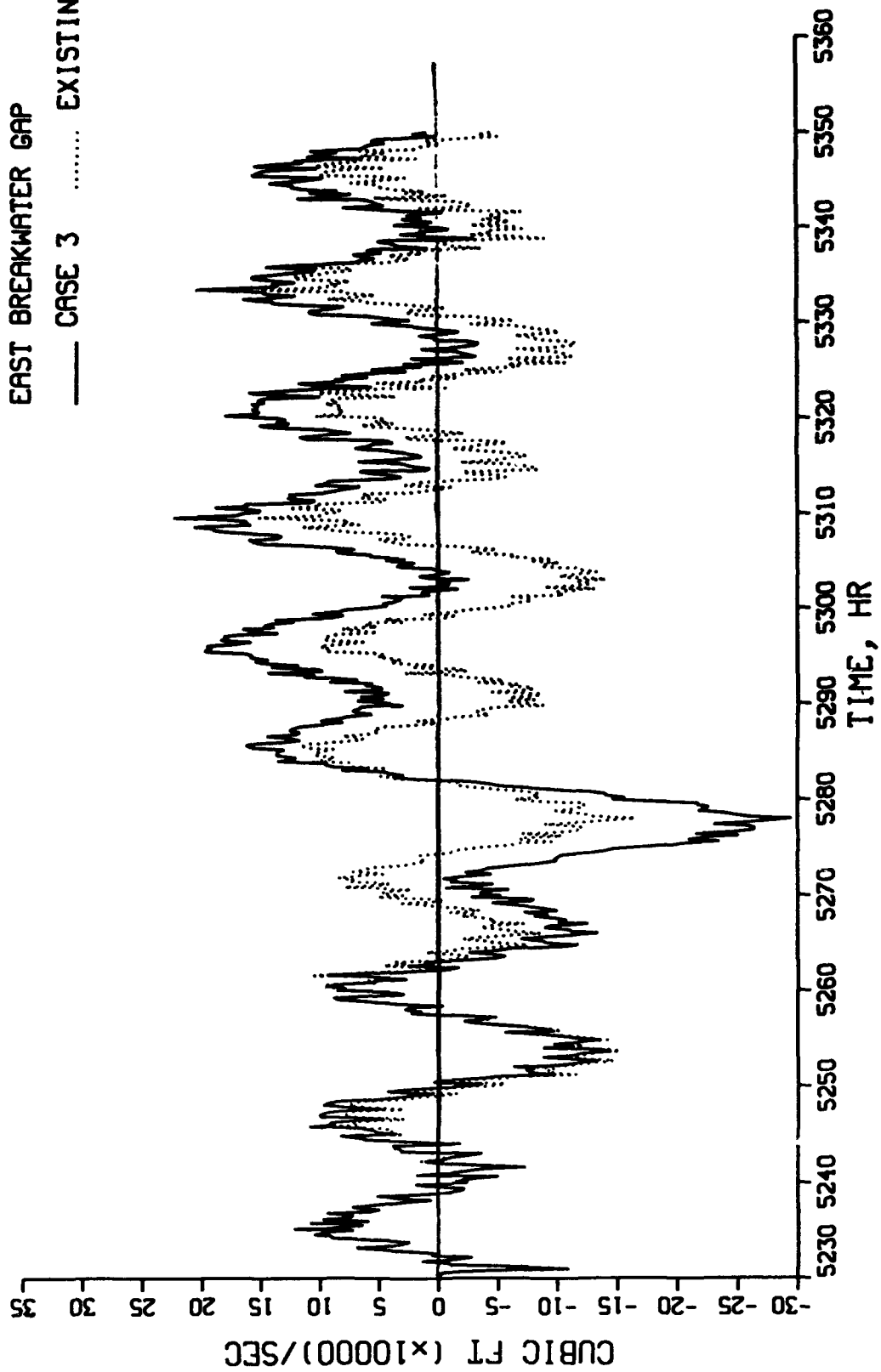
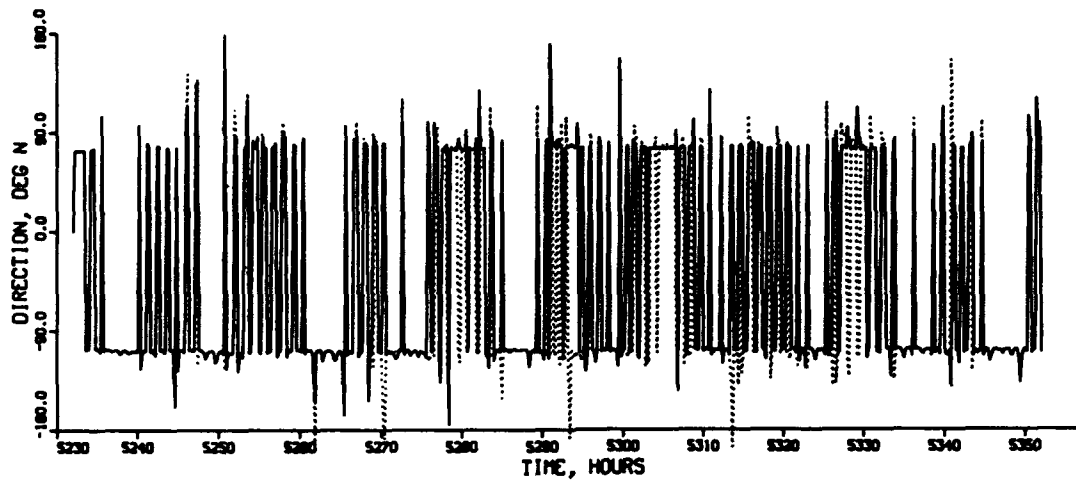
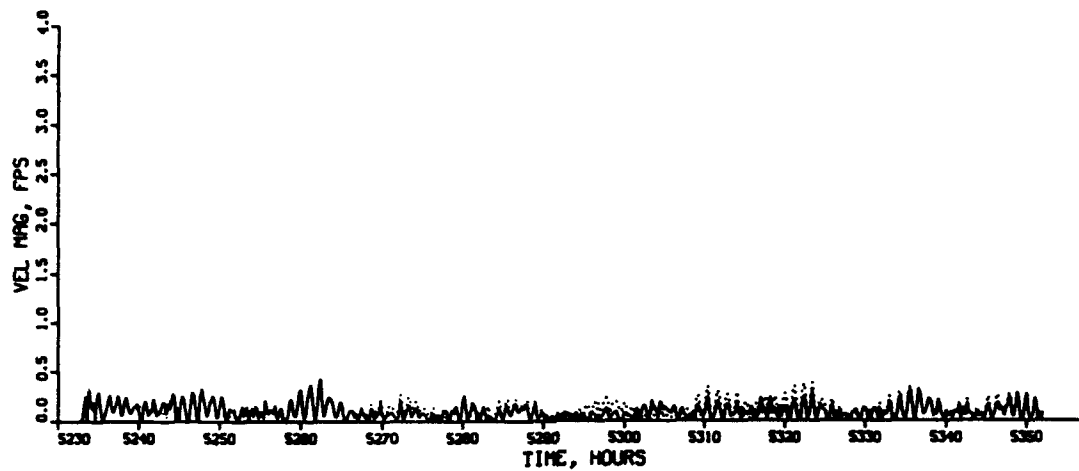


PLATE 124

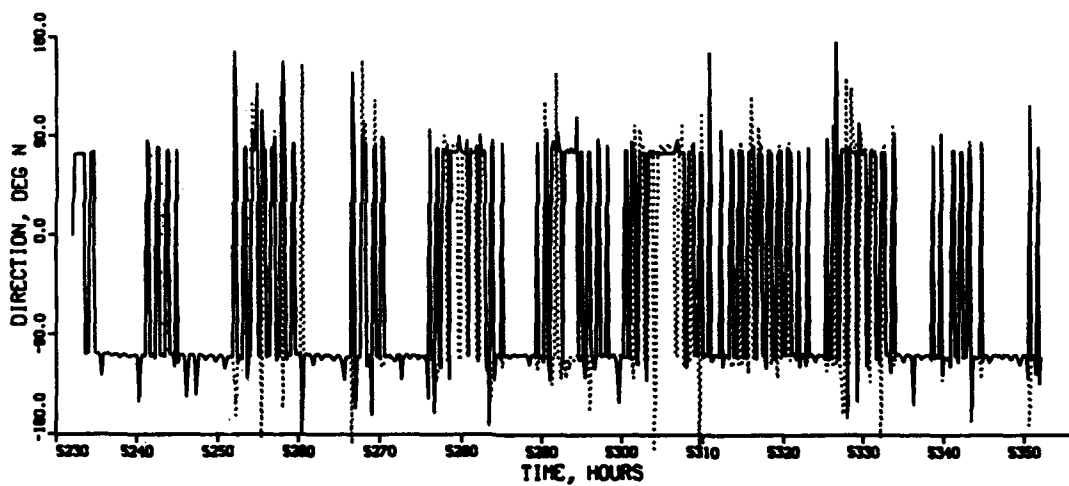
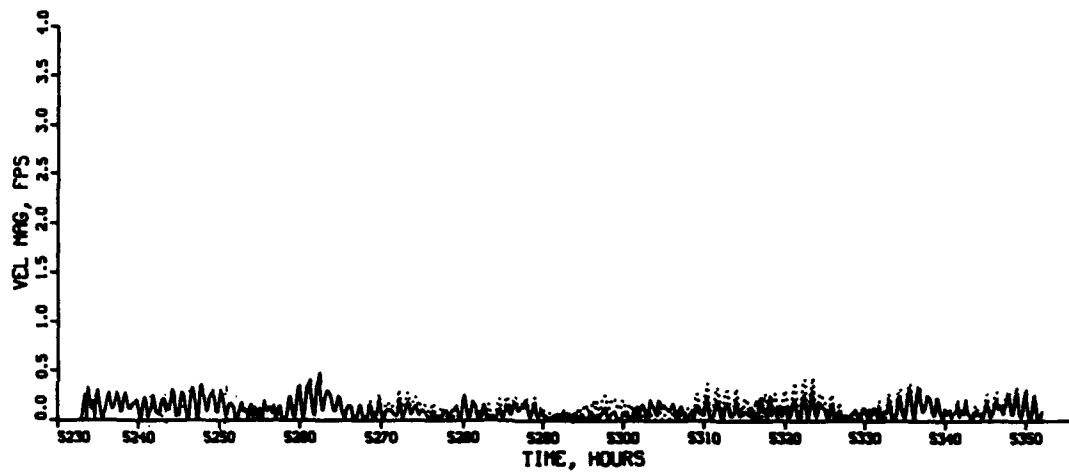
RANGE NO. 7
EAST BREAKWATER GAP
— CASE 3 EXISTING

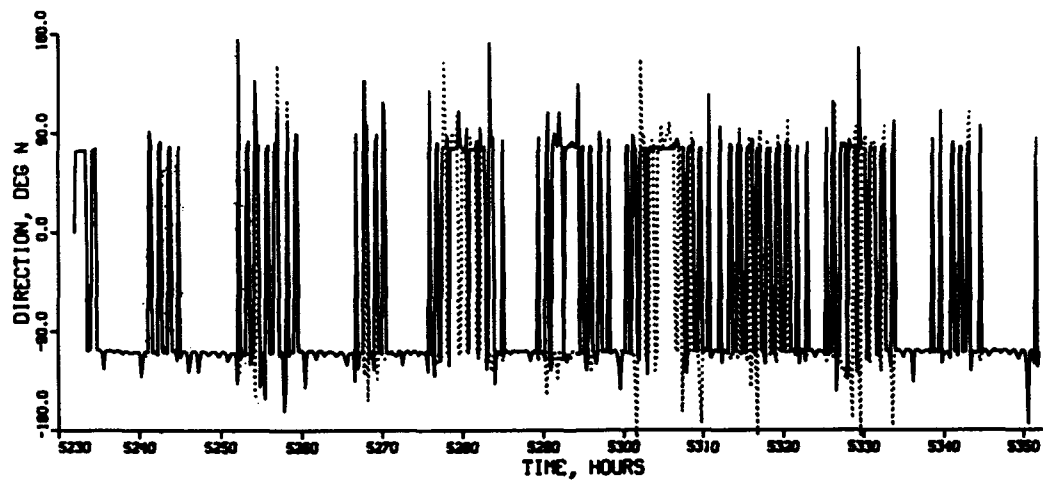
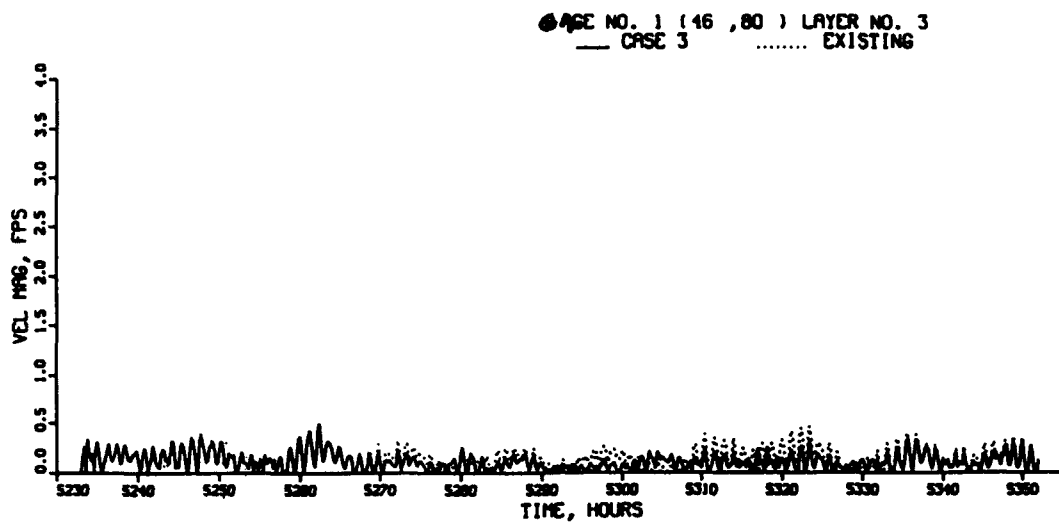


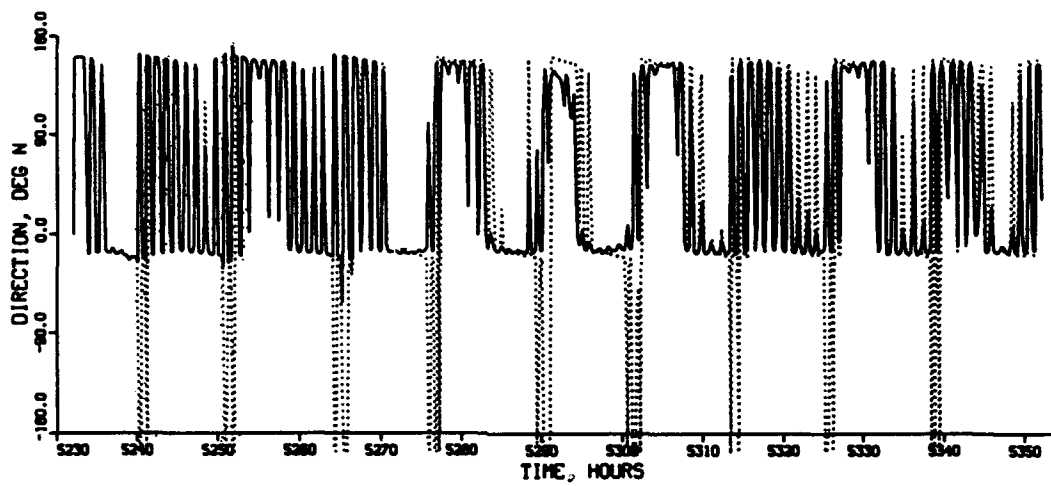
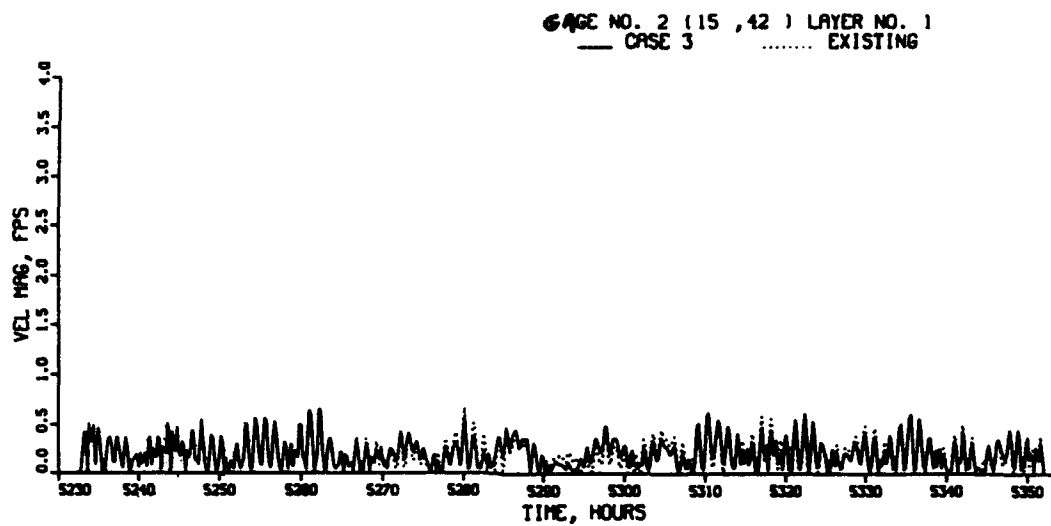
6 AGE NO. 1 (46 , 80) LAYER NO. 1
— CASE 3 EXISTING



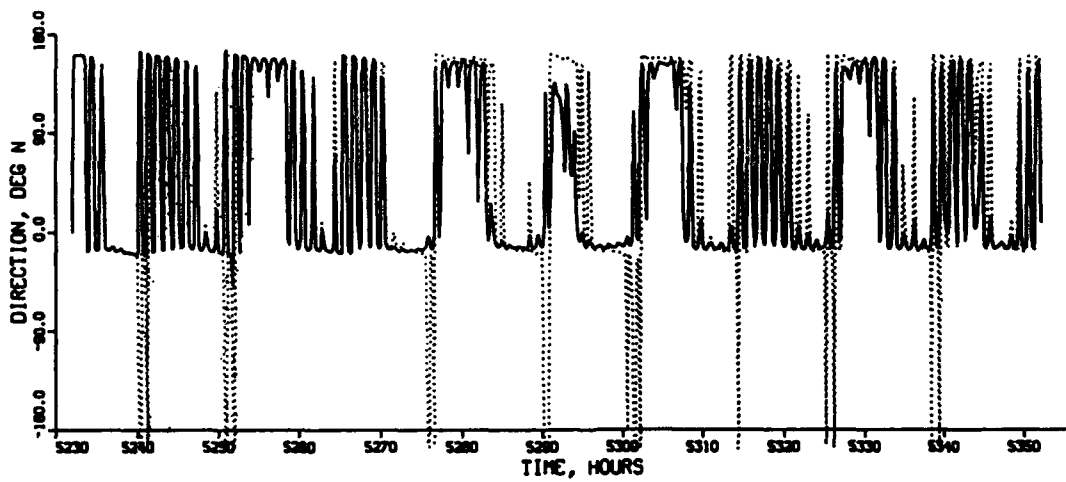
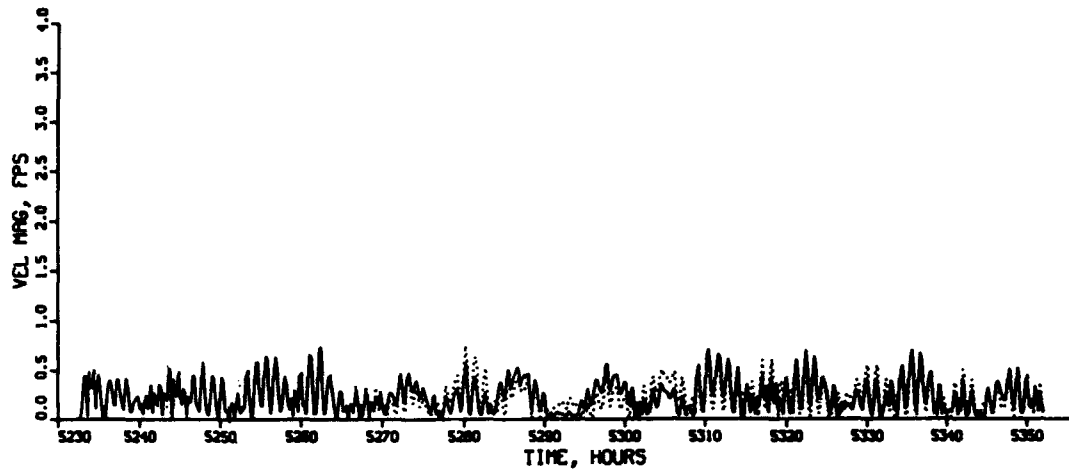
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— CASE 3 EXISTING

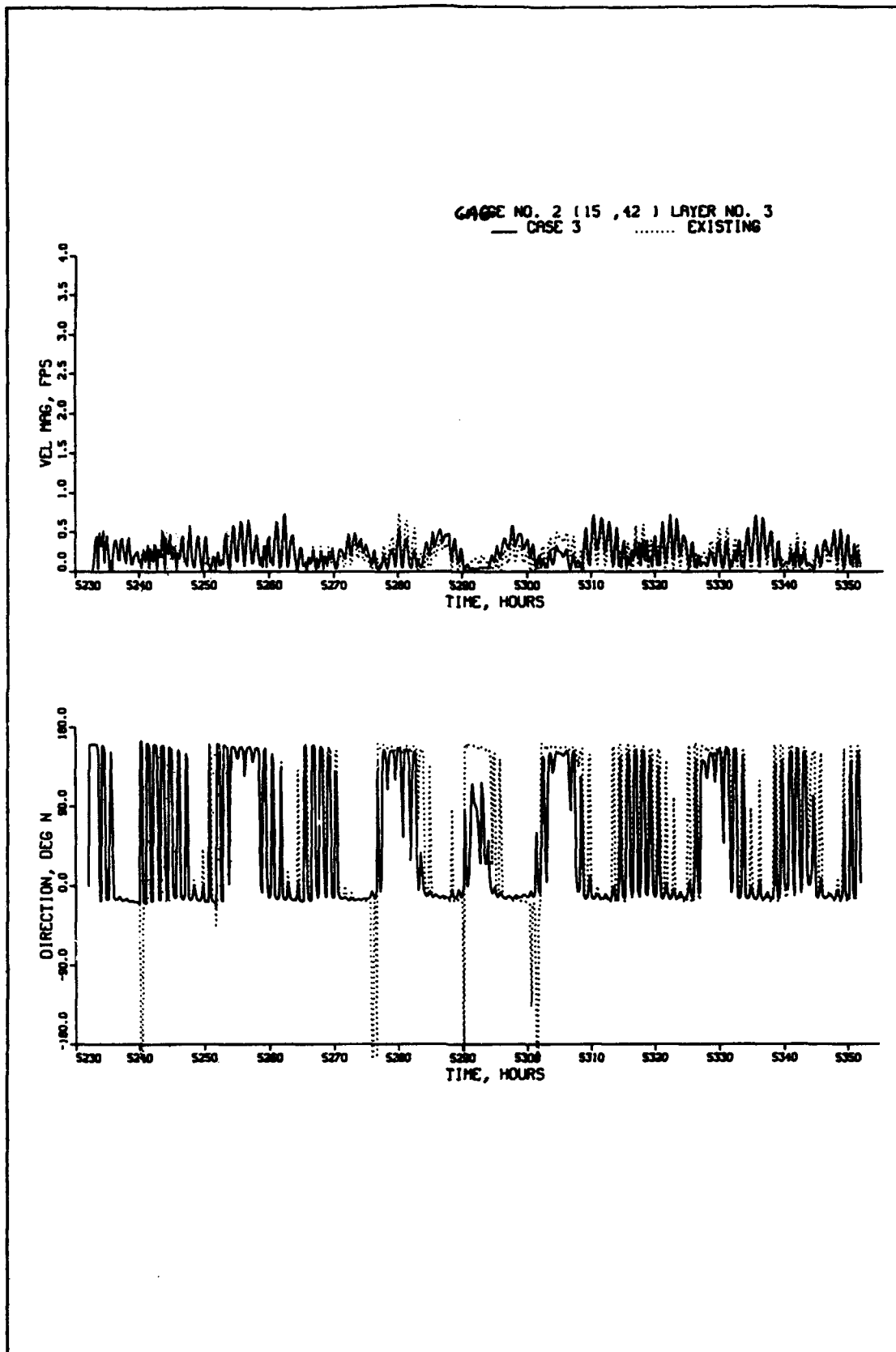


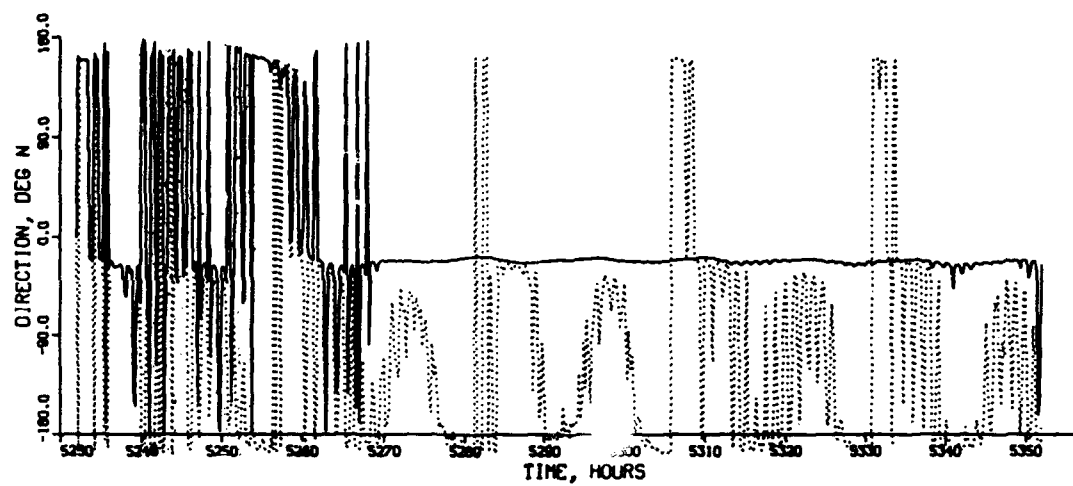
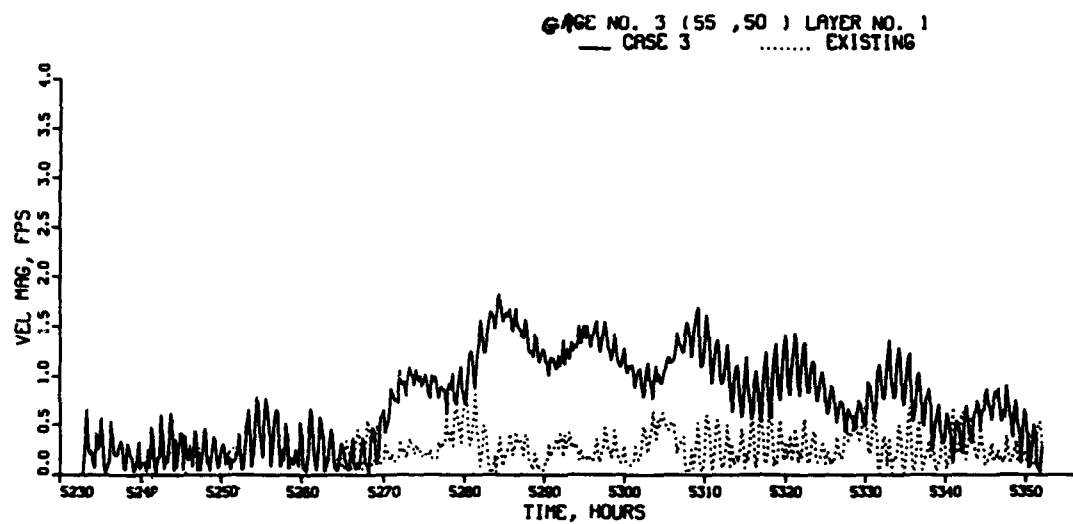




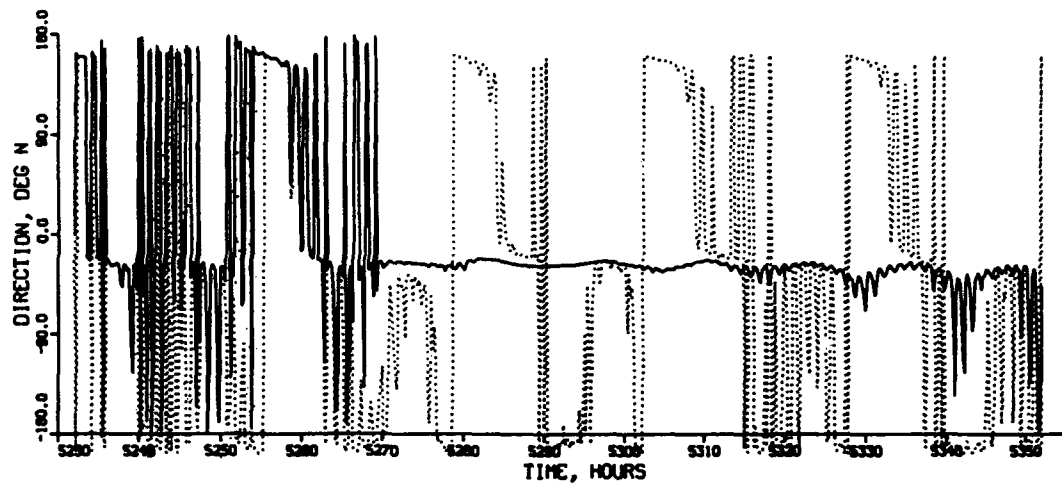
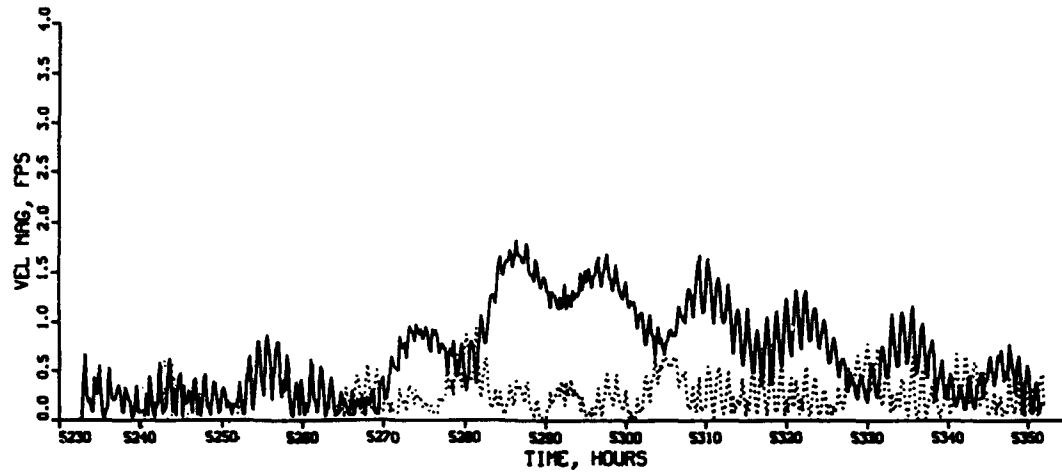
PAGE NO. 2 (15, 42) LAYER NO. 2
— CASE 3 EXISTING







GAGE NO. 3 (55, 50) LAYER NO. 2
— CASE 3 EXISTING



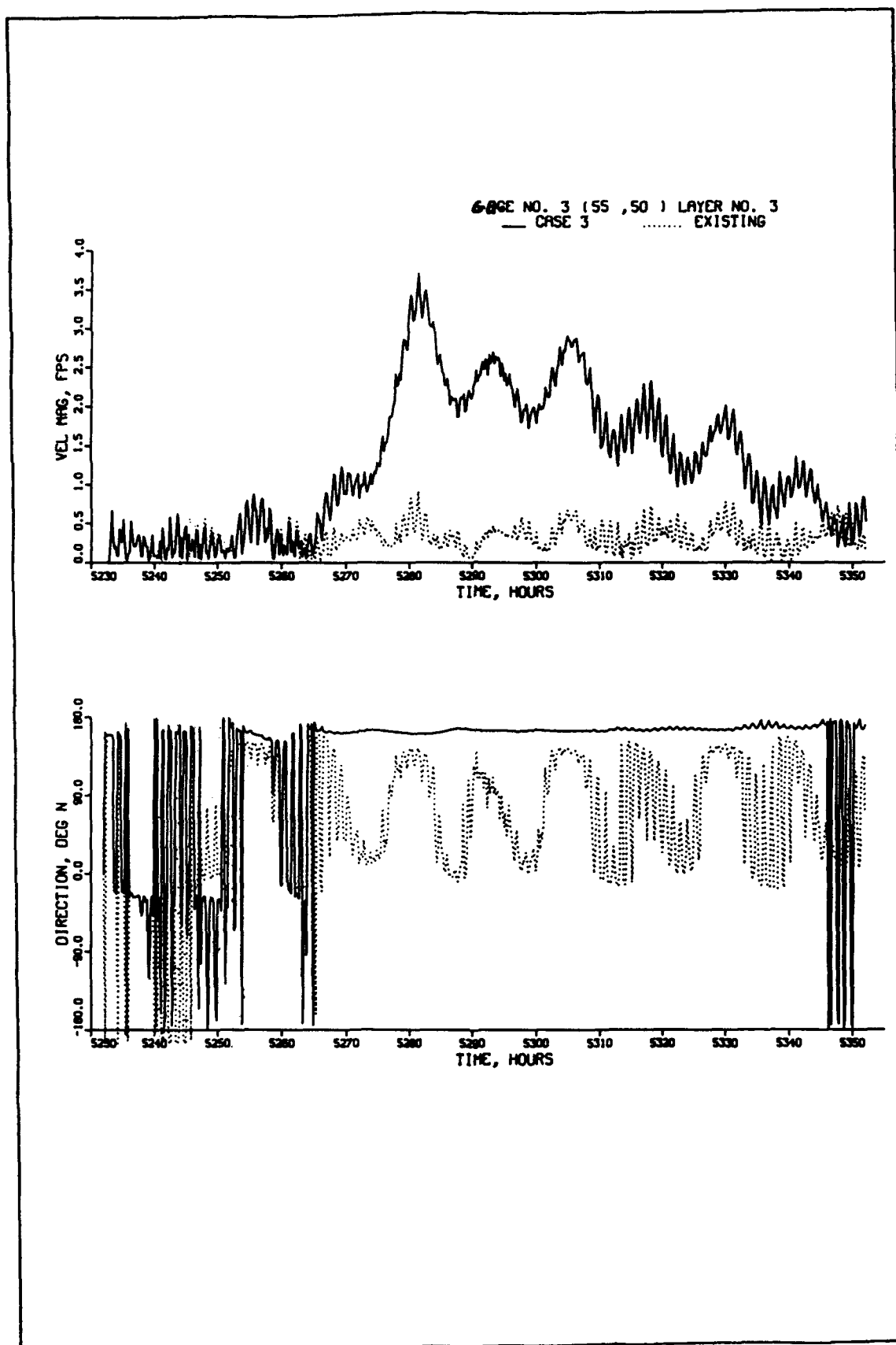
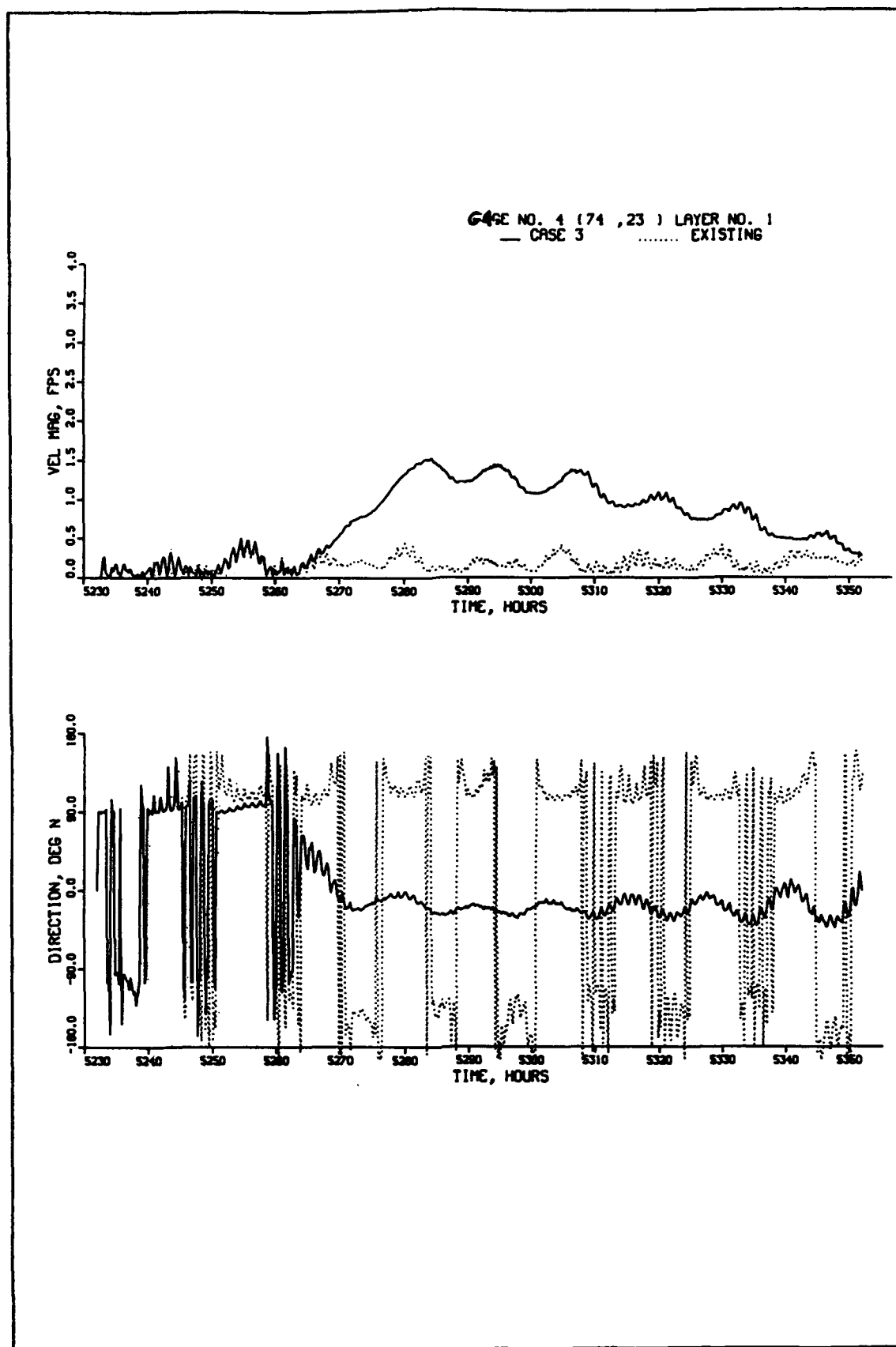
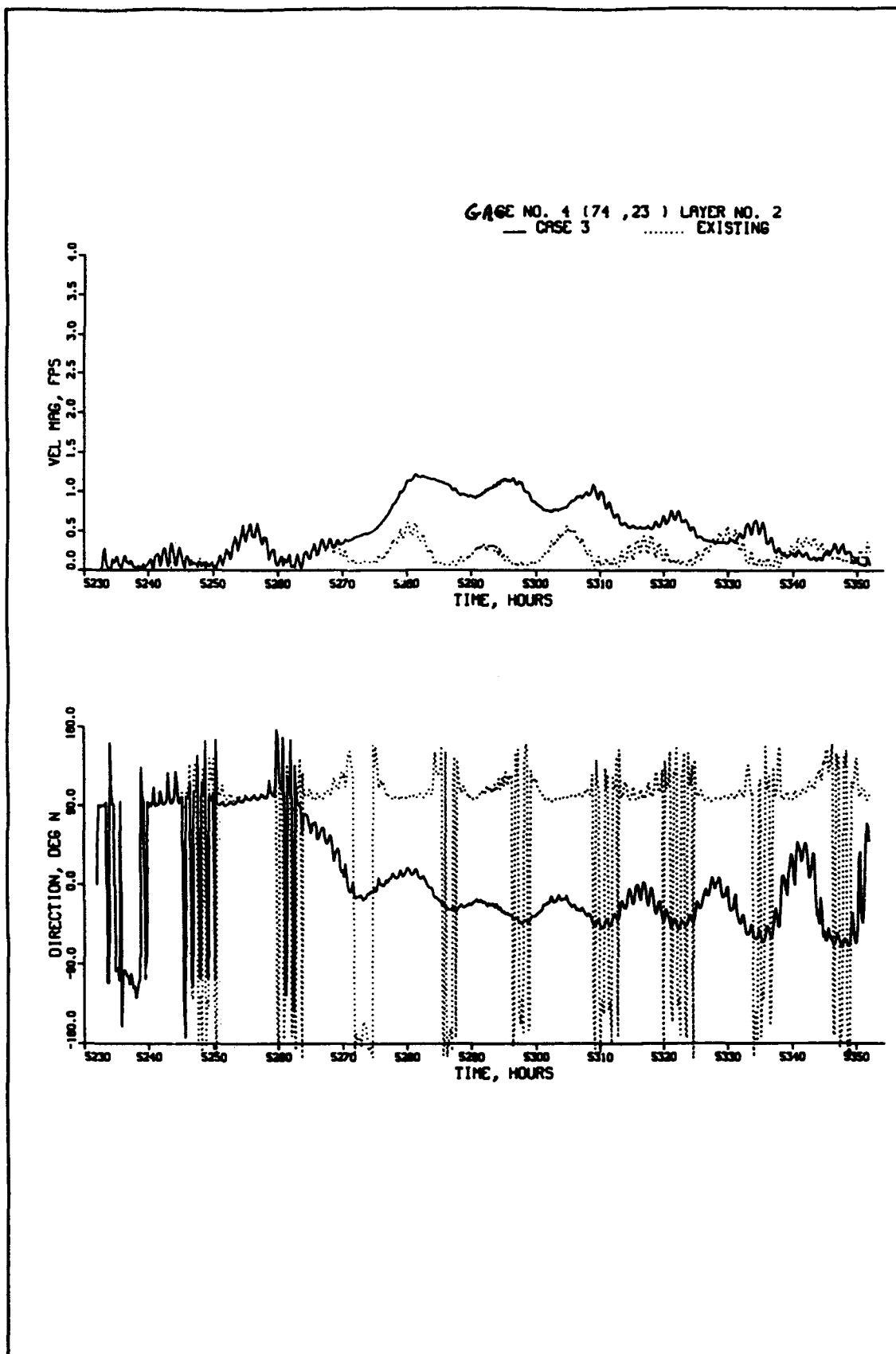
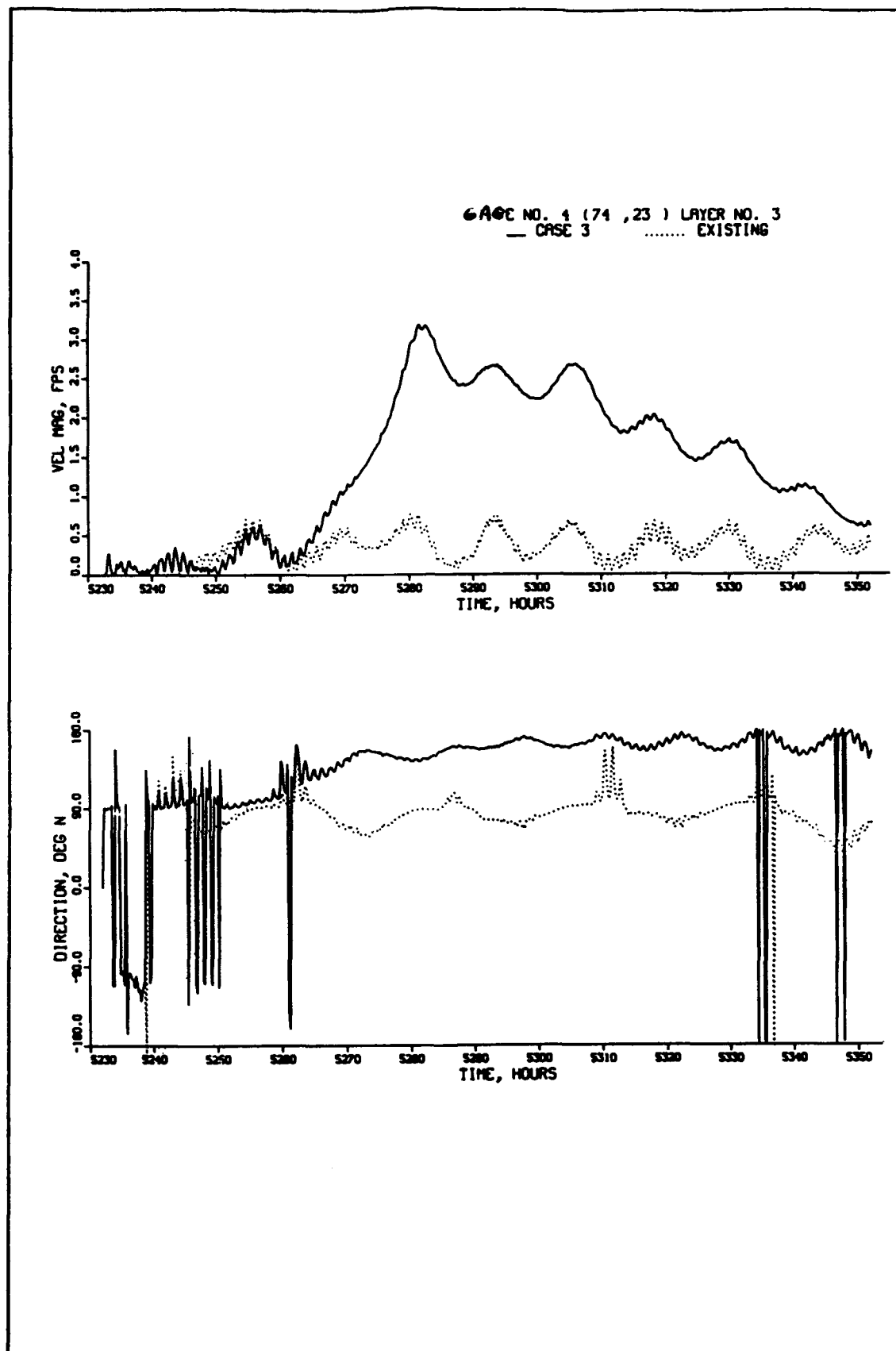


PLATE 134







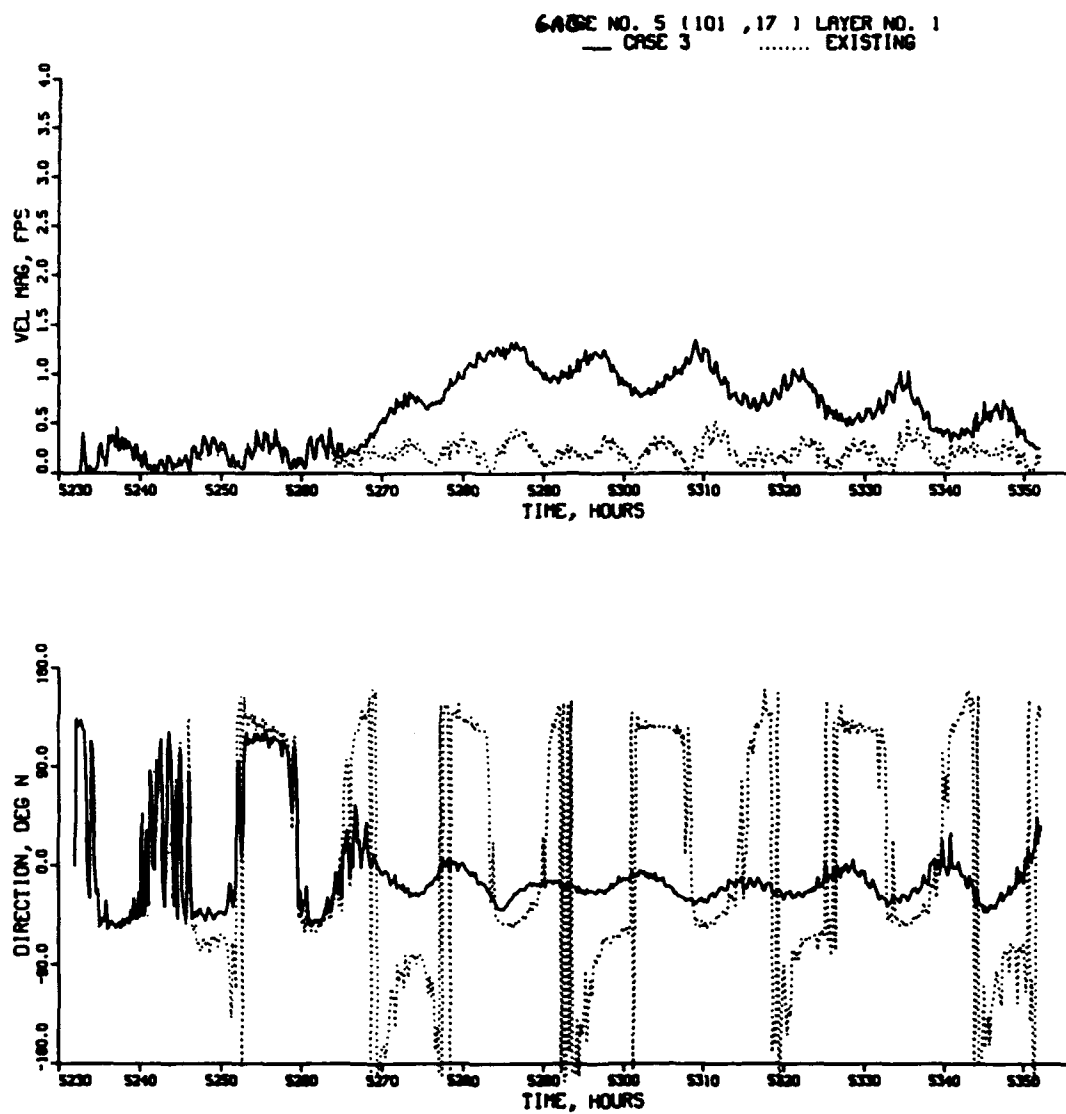
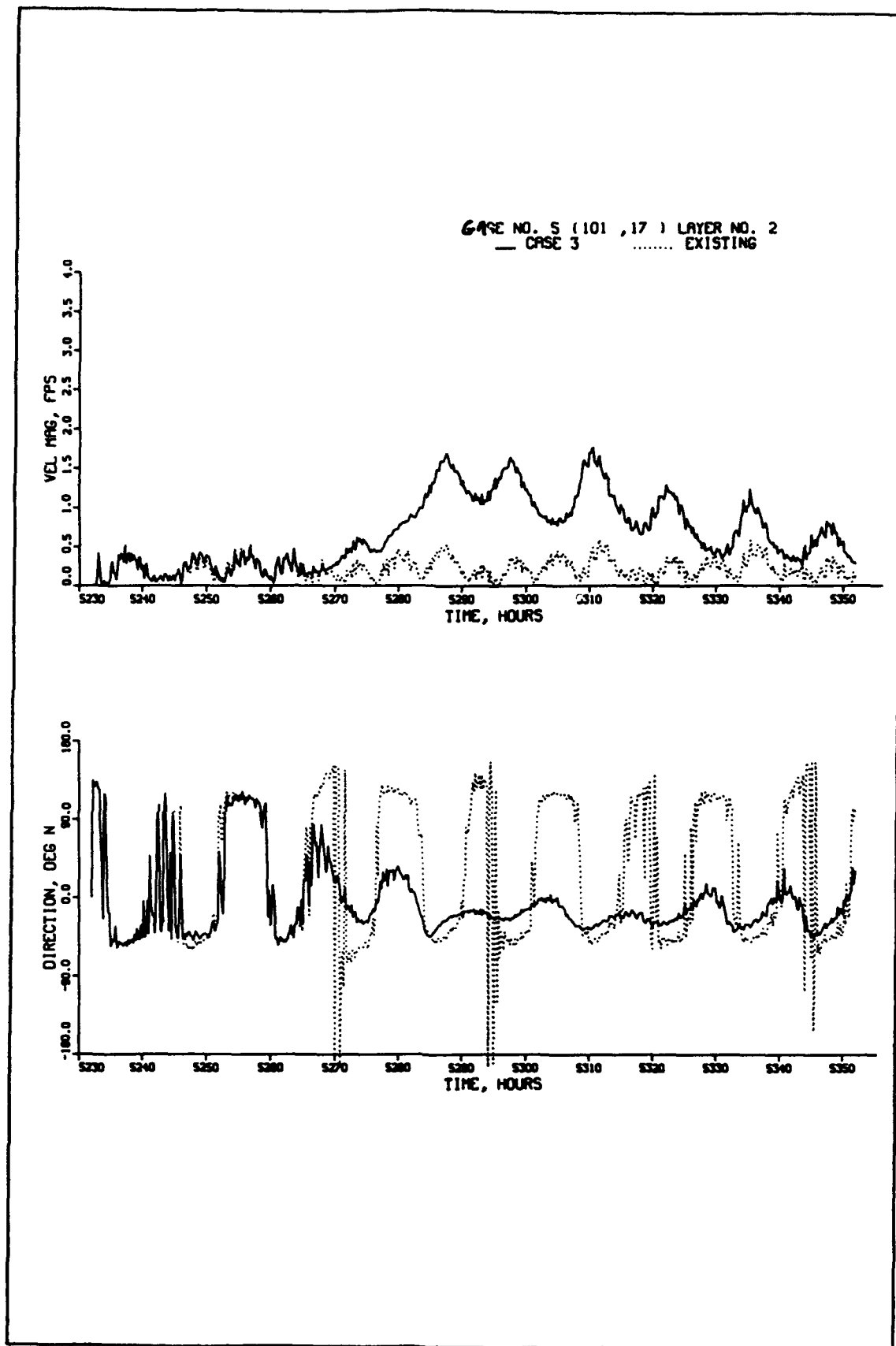
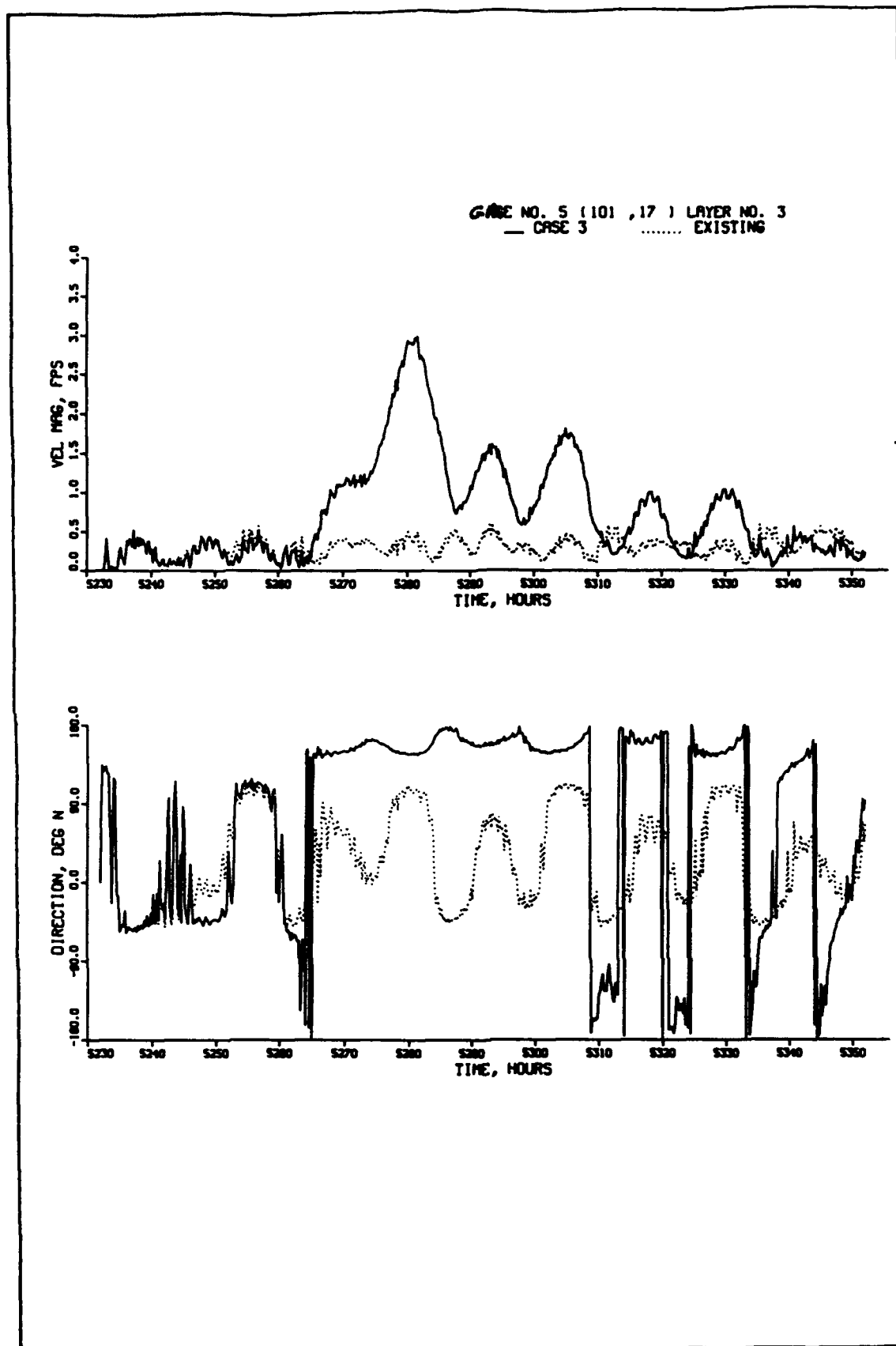
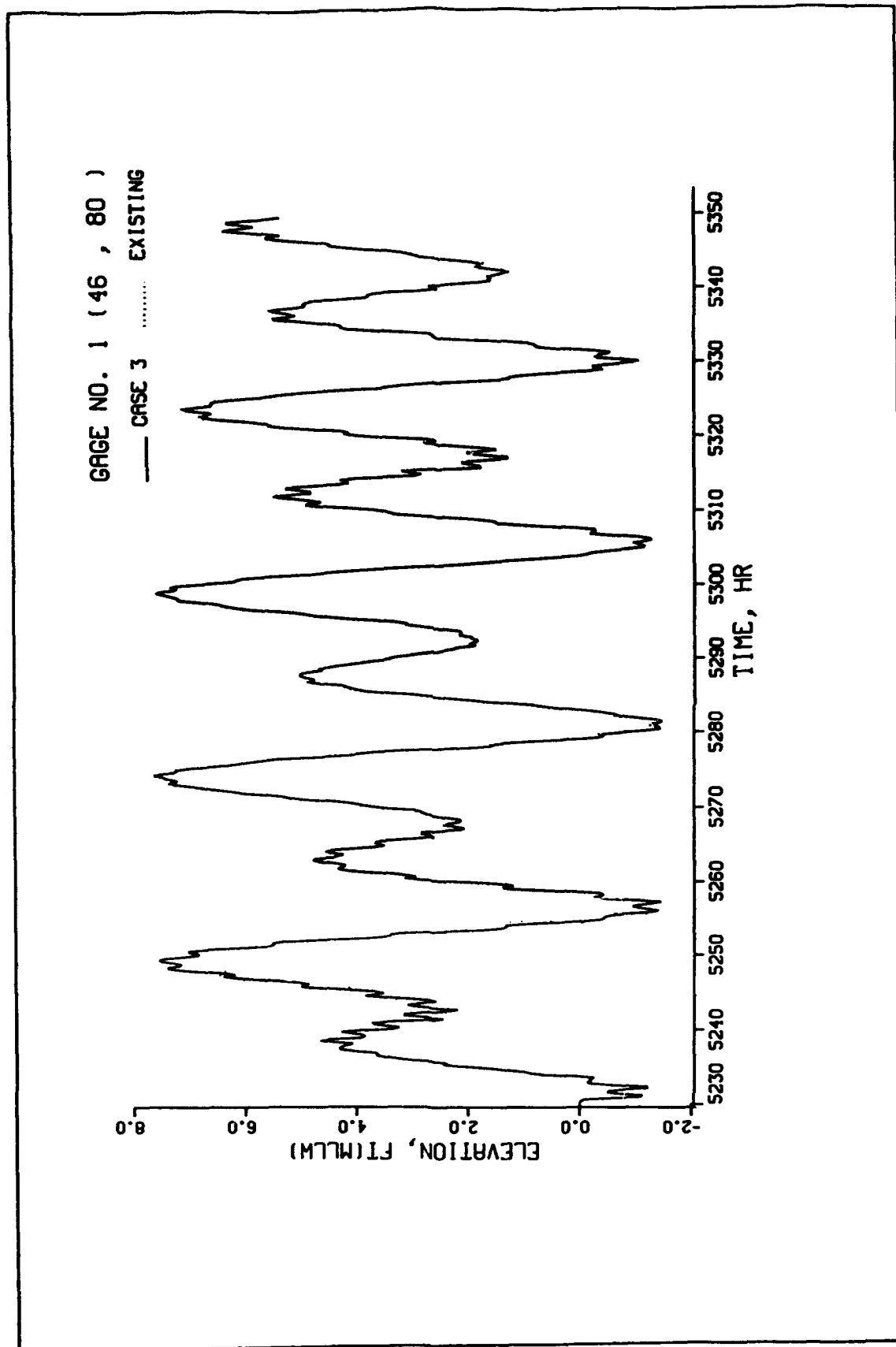


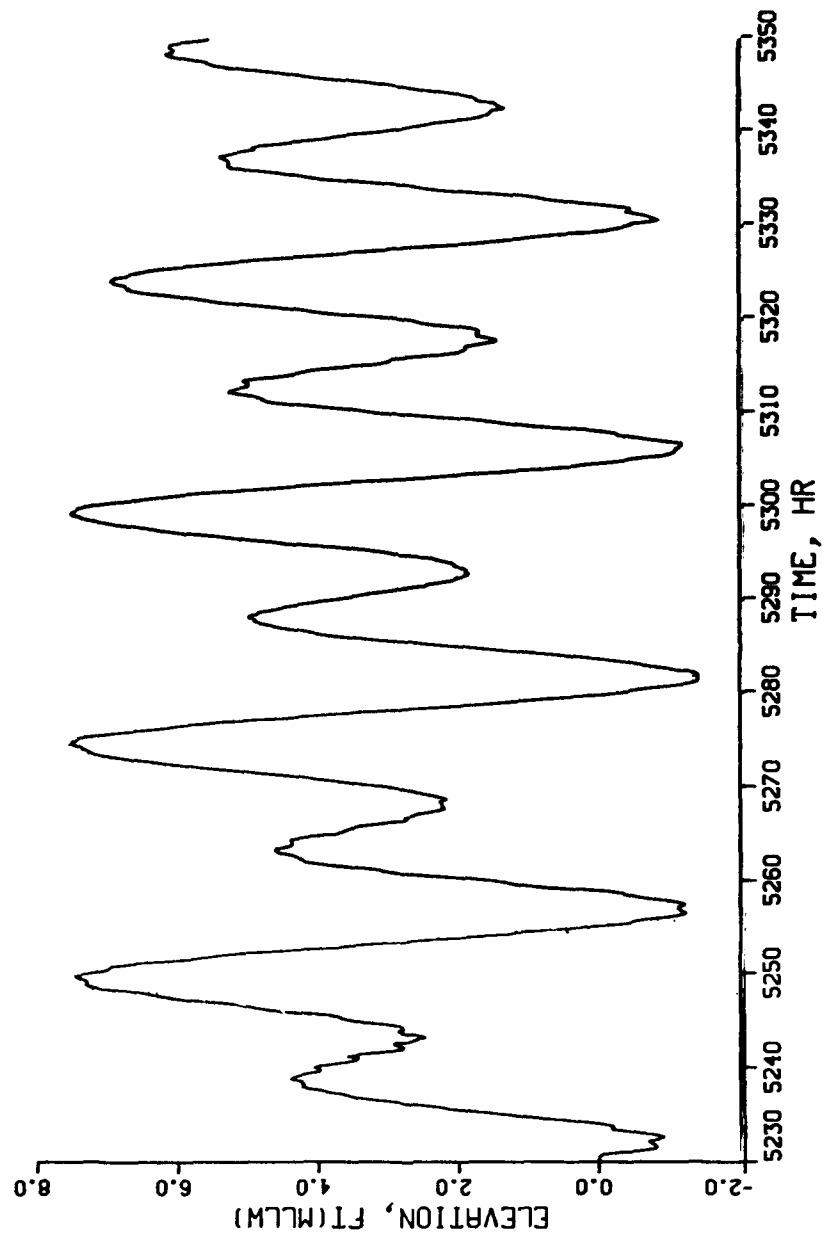
PLATE 138



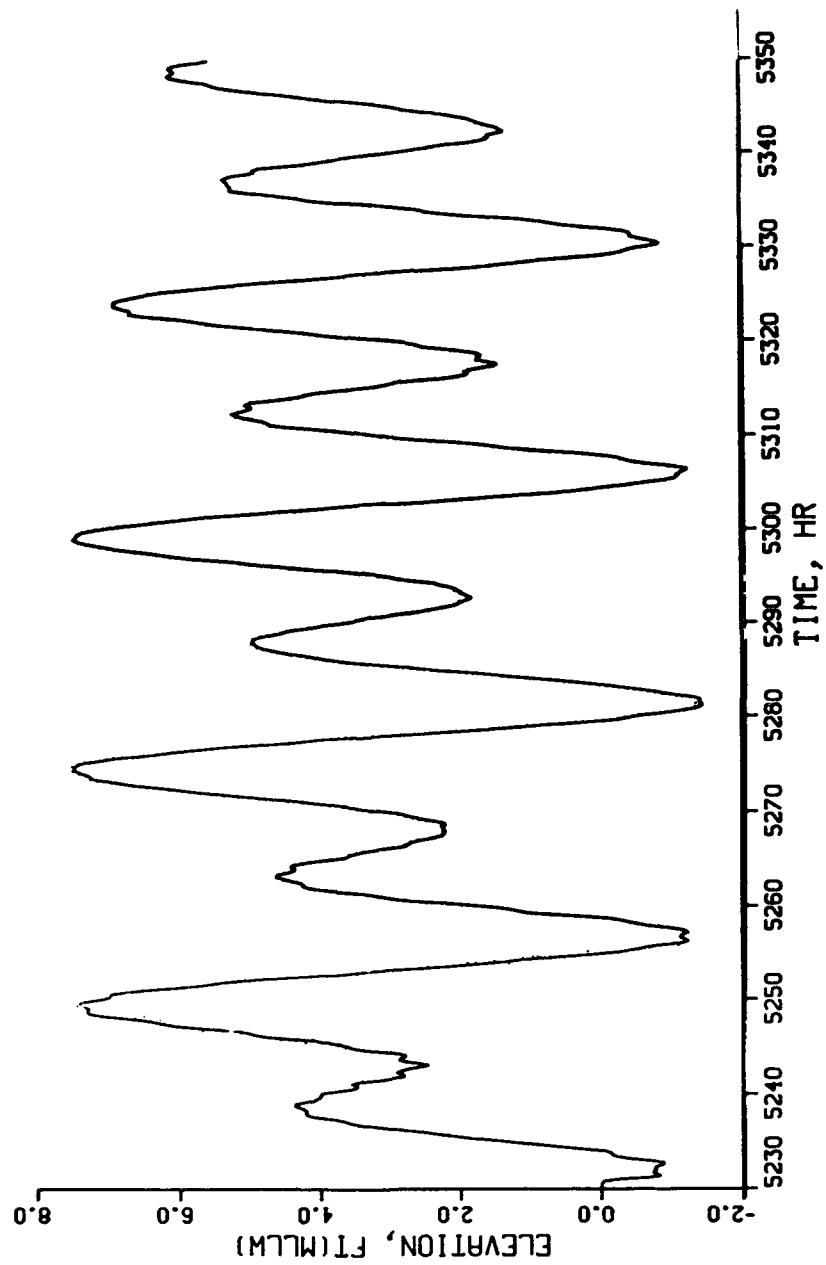




GAGE NO. 2 (15 , 42)
— CASE 3 EXISTING

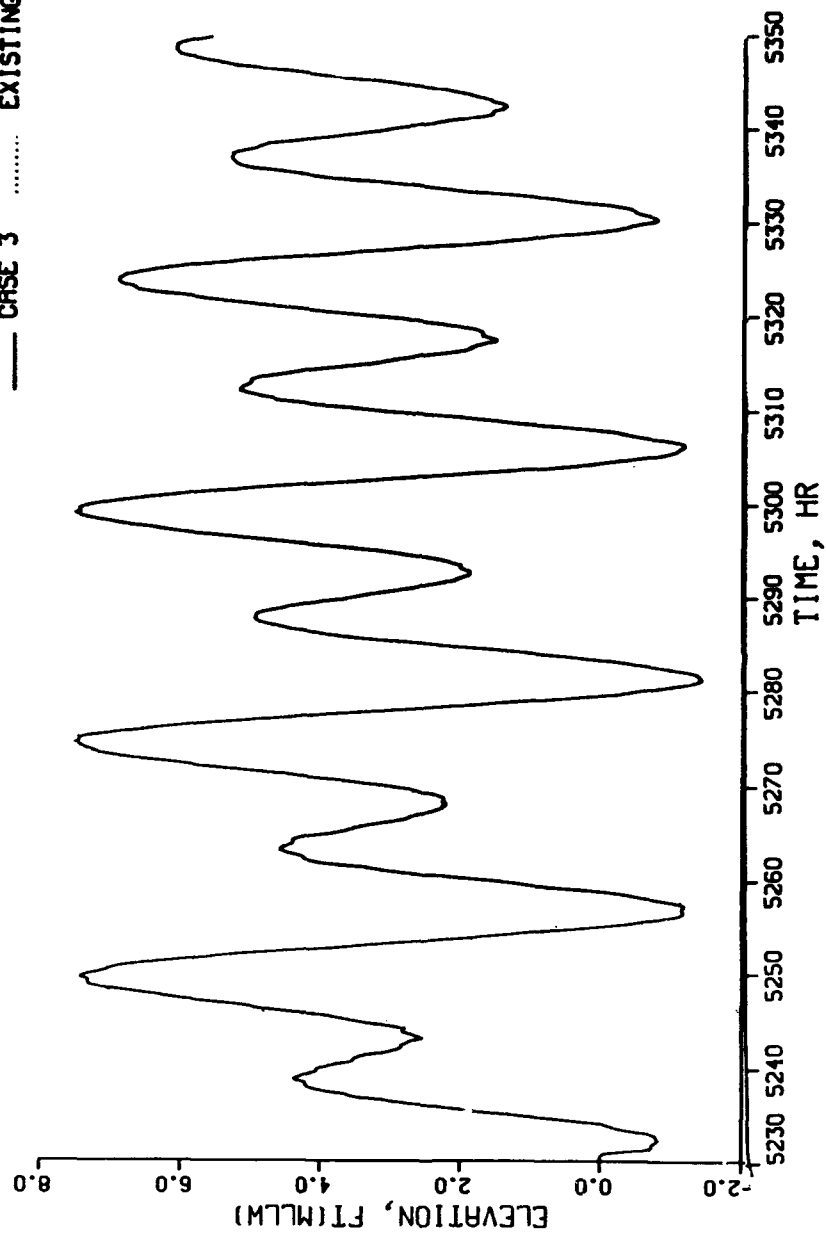


GAGE NO. 3 (55 , 50)
— CASE 3 EXISTING



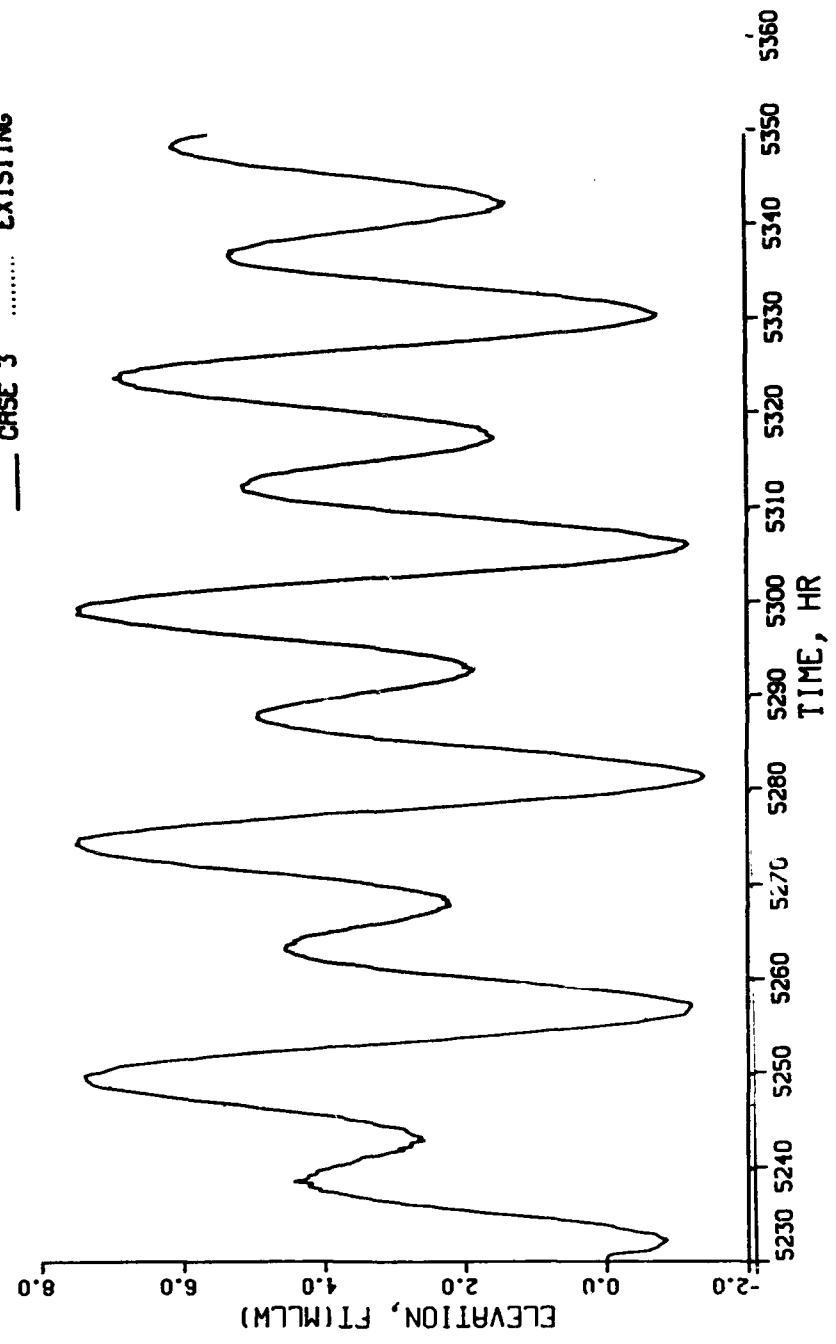
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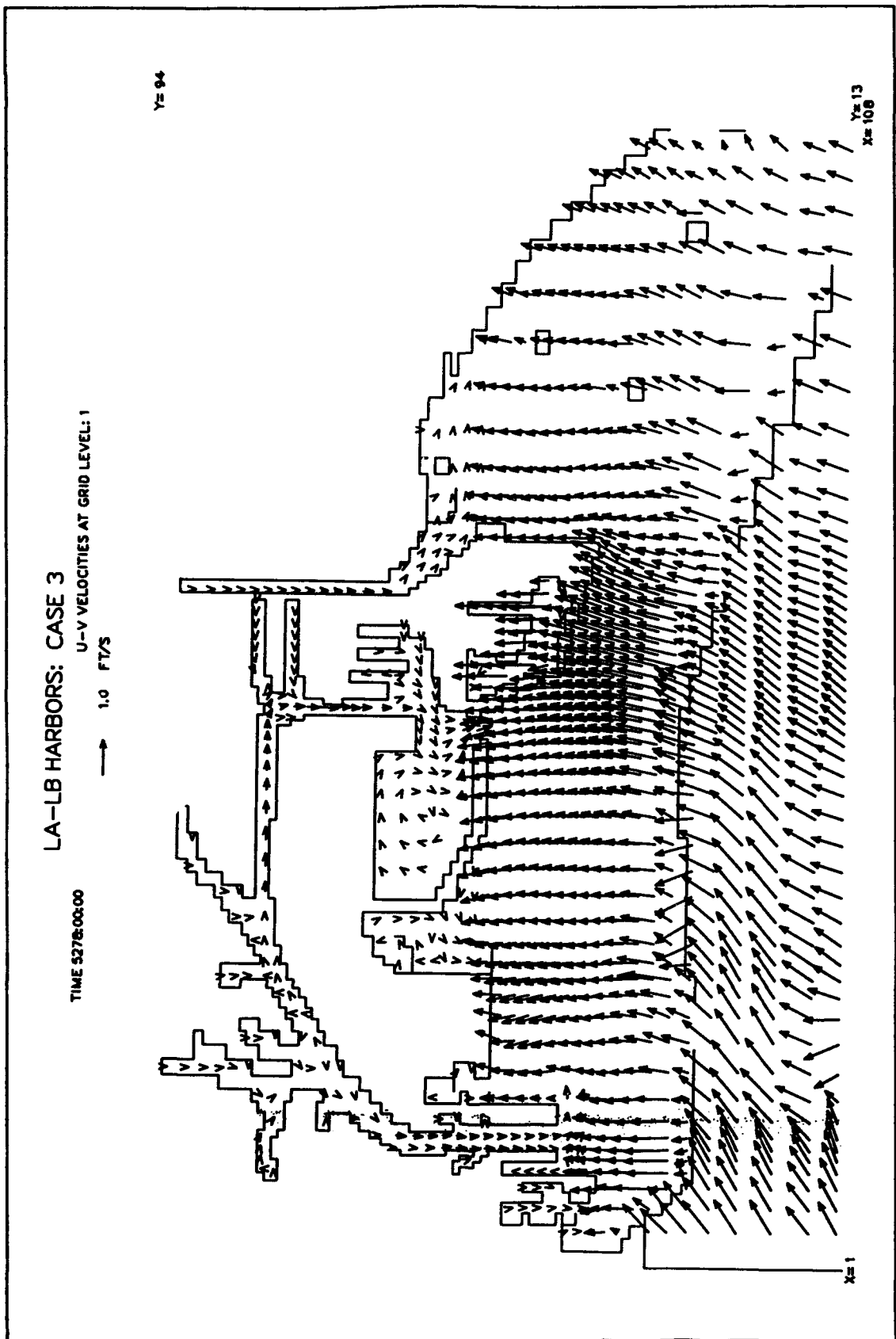
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GAGE NO. 5 (101 , 17)

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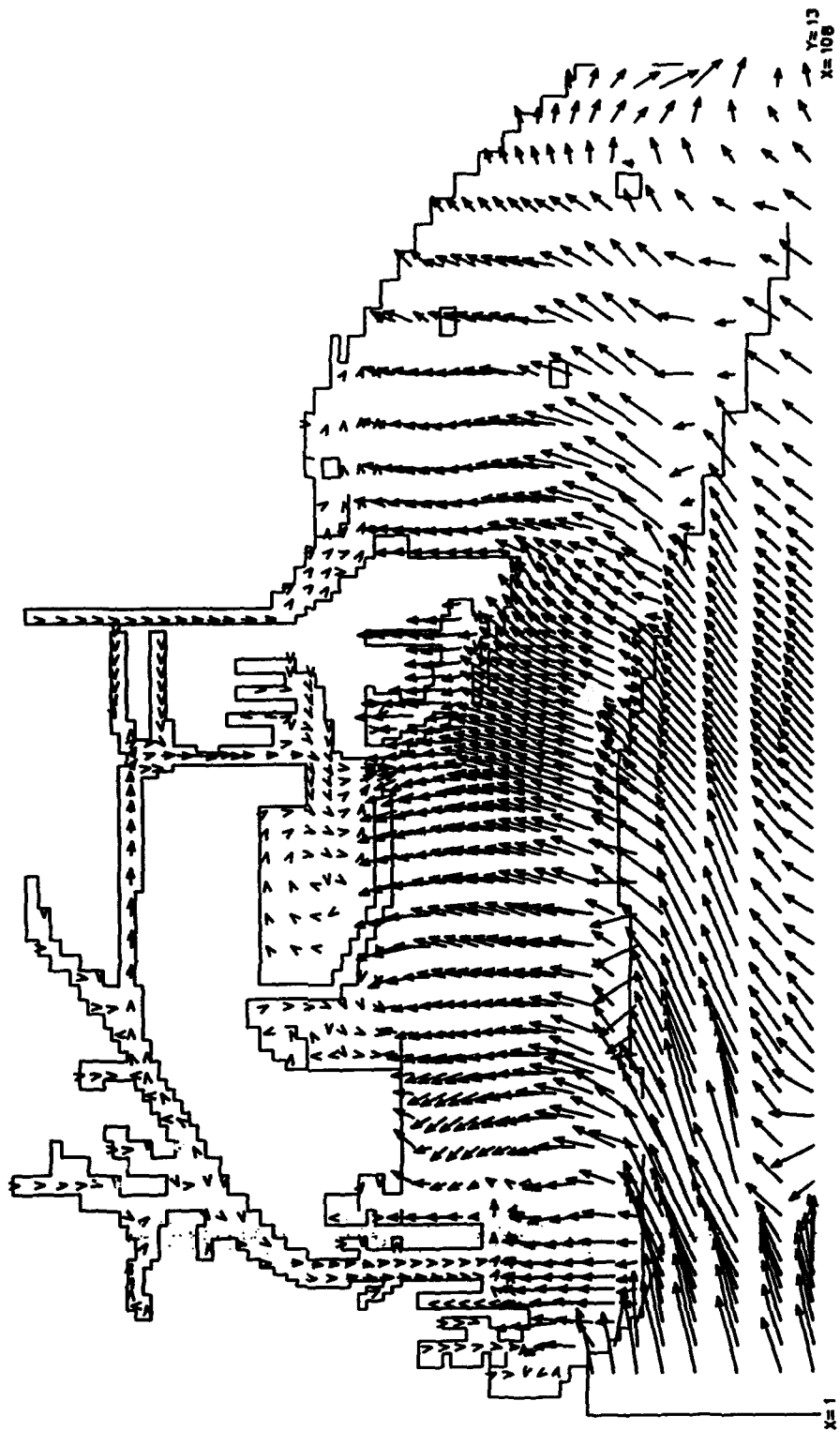


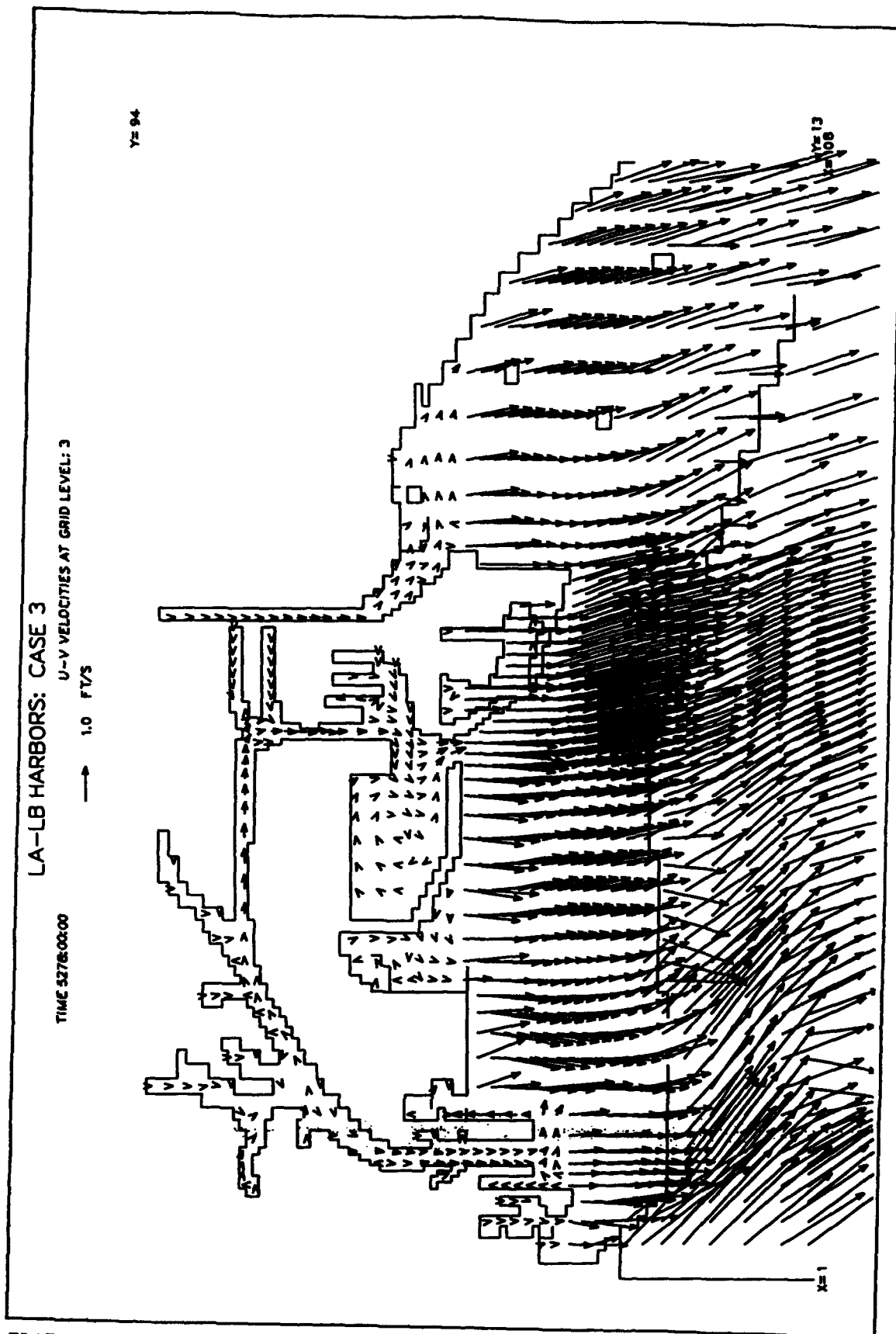


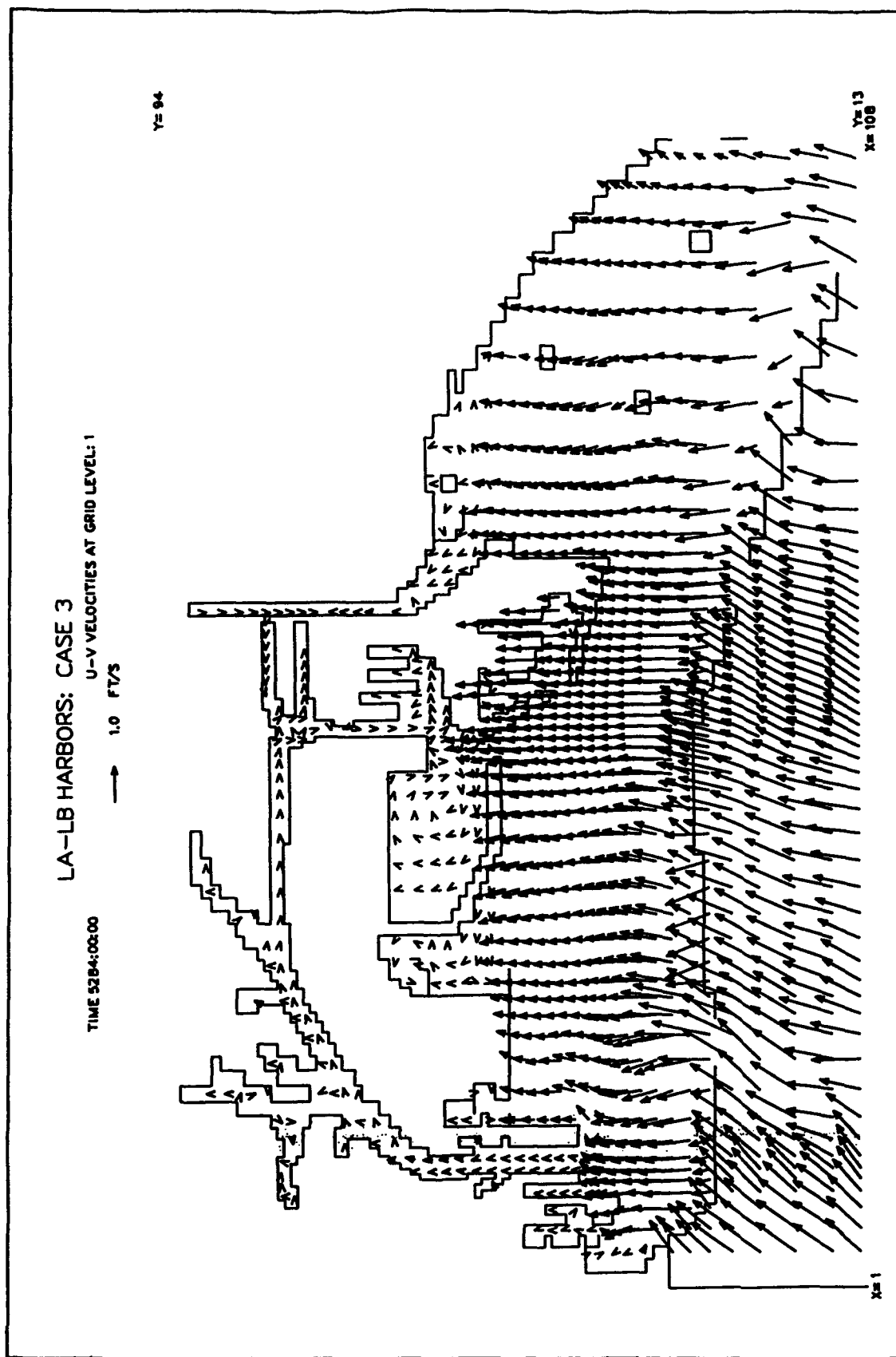
LA-LB HARBORS: CASE 3

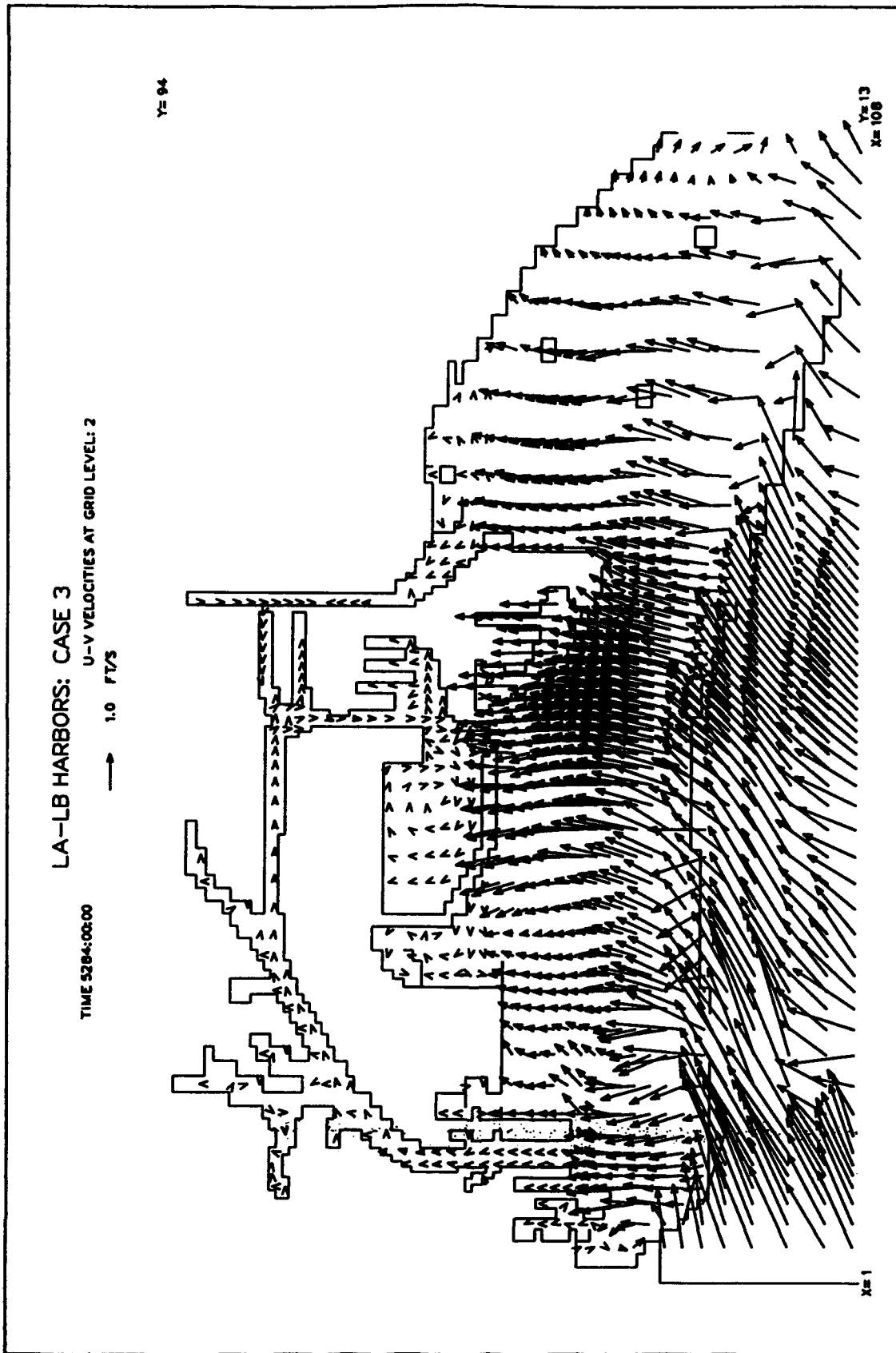
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→ 1.0 FT/S

Y=94









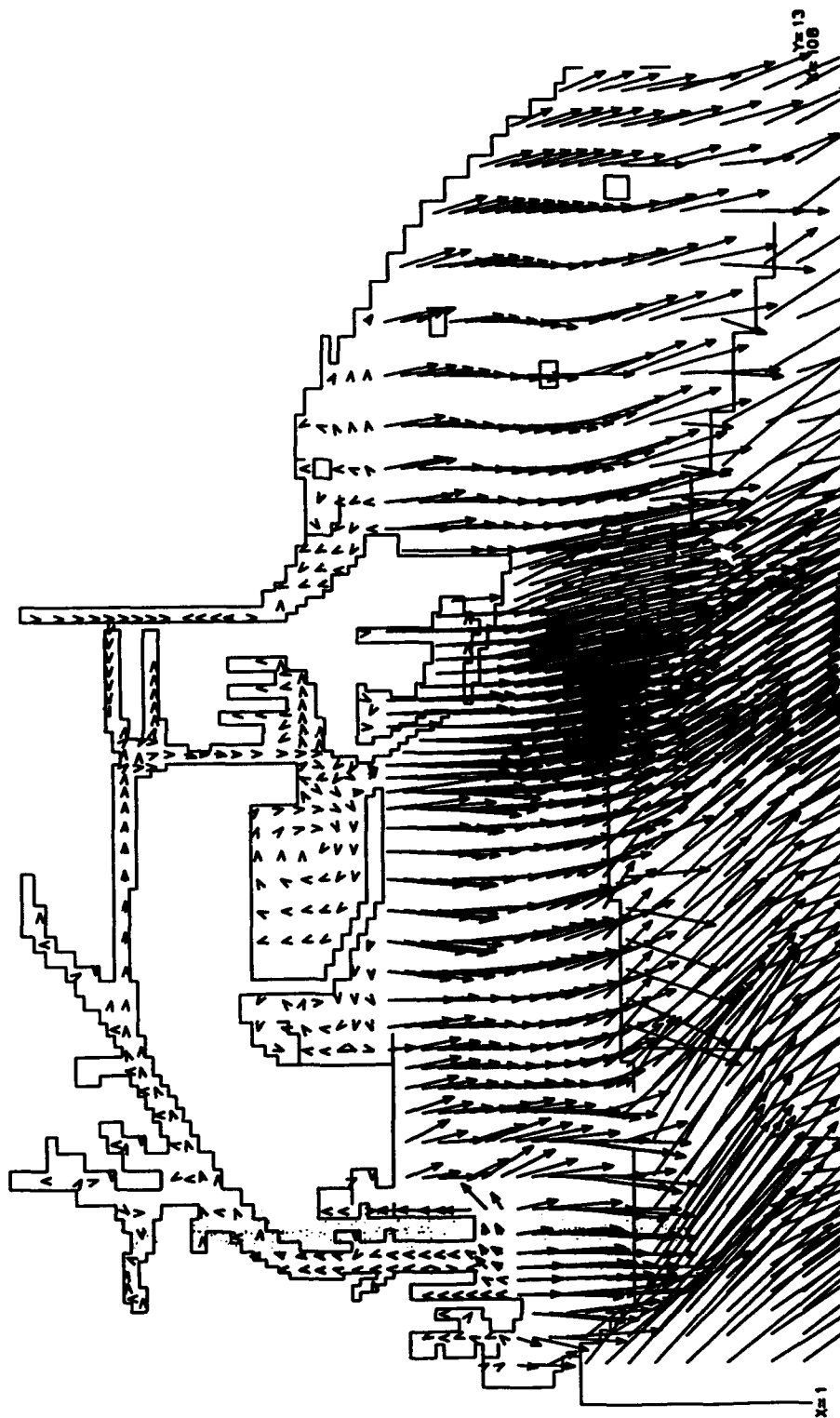
LA-LB HARBORS: CASE 3

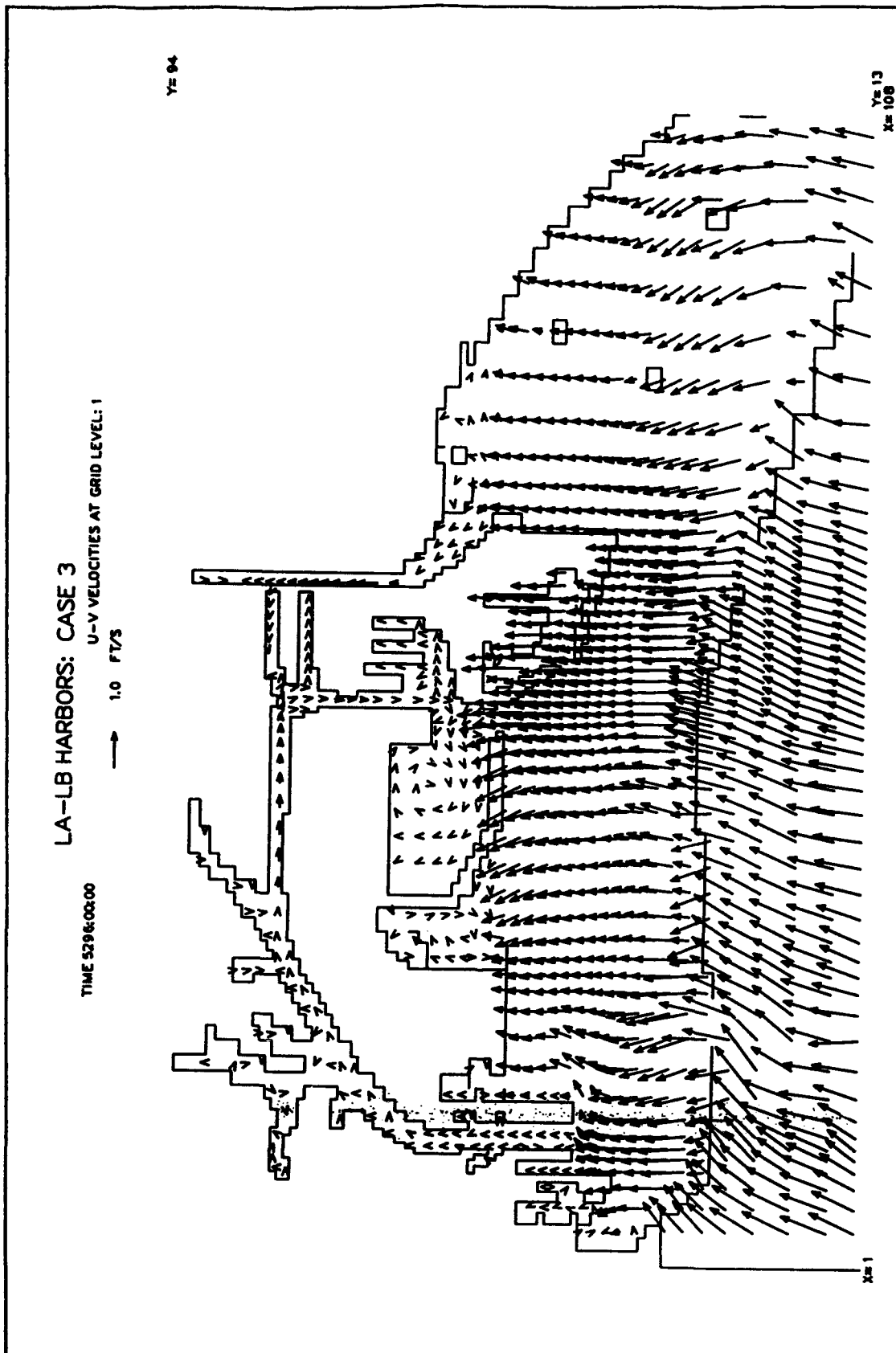
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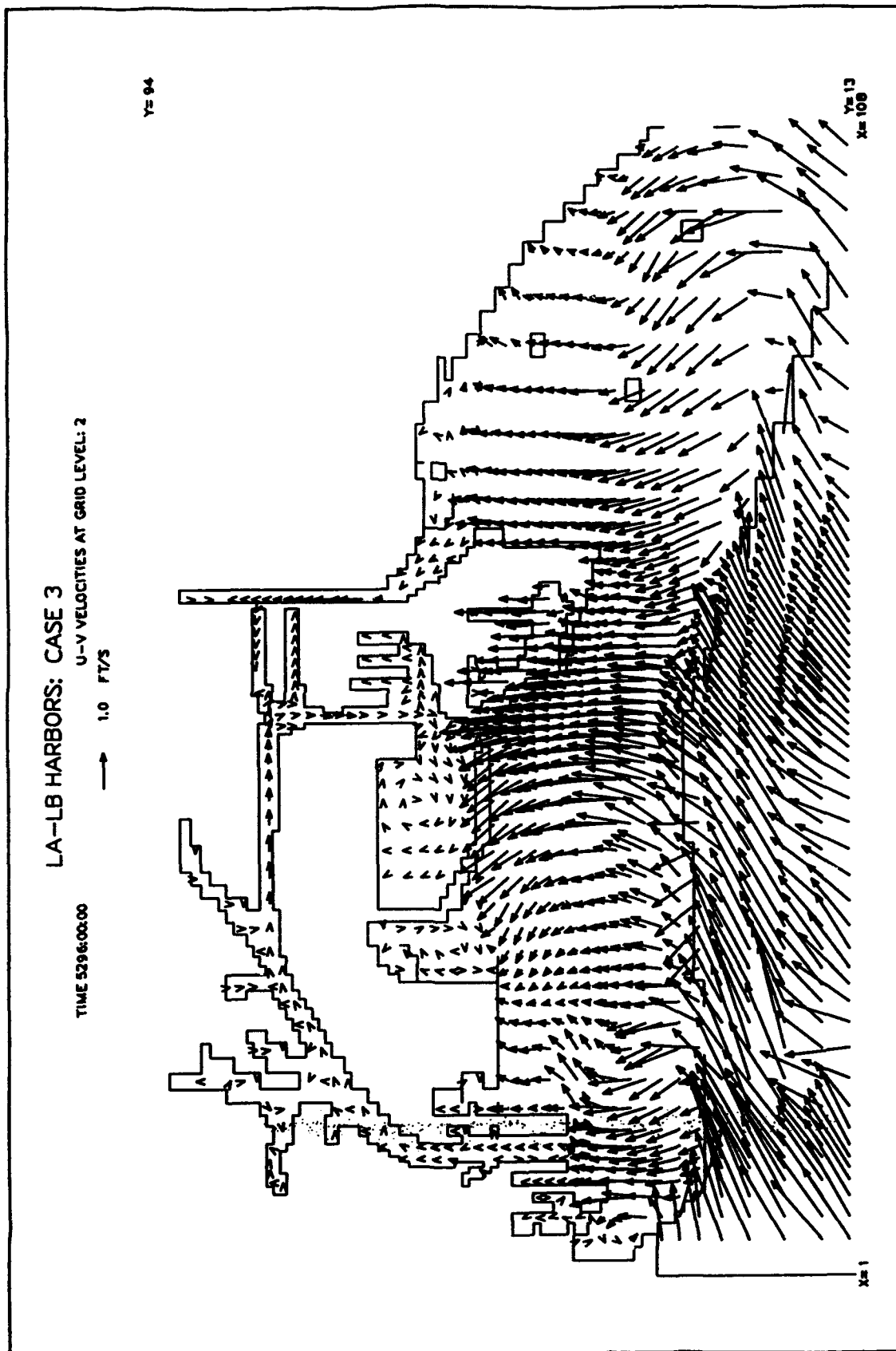
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→ 1.0 FT/S

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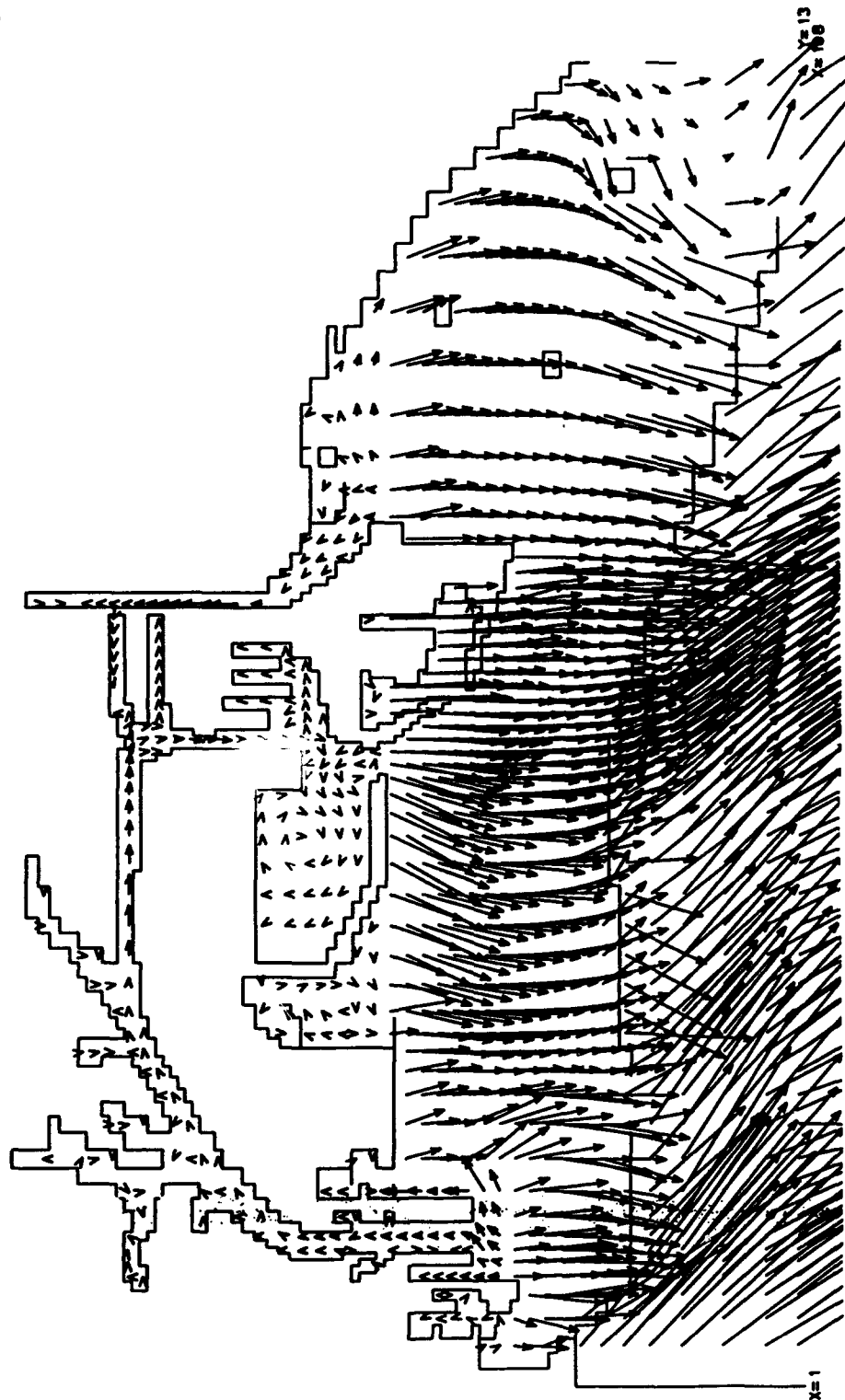
LA-LB HARBORS: CASE 3

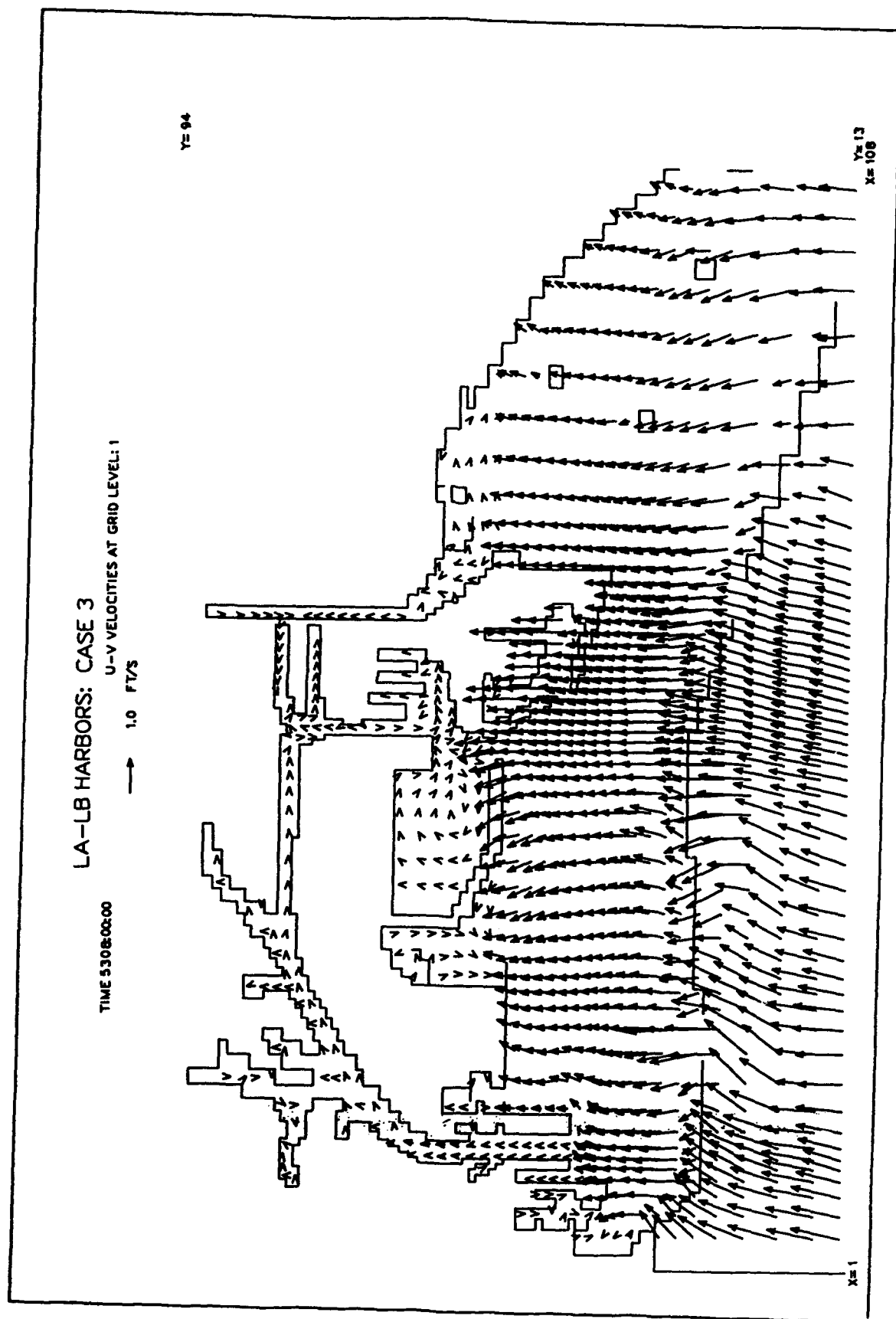
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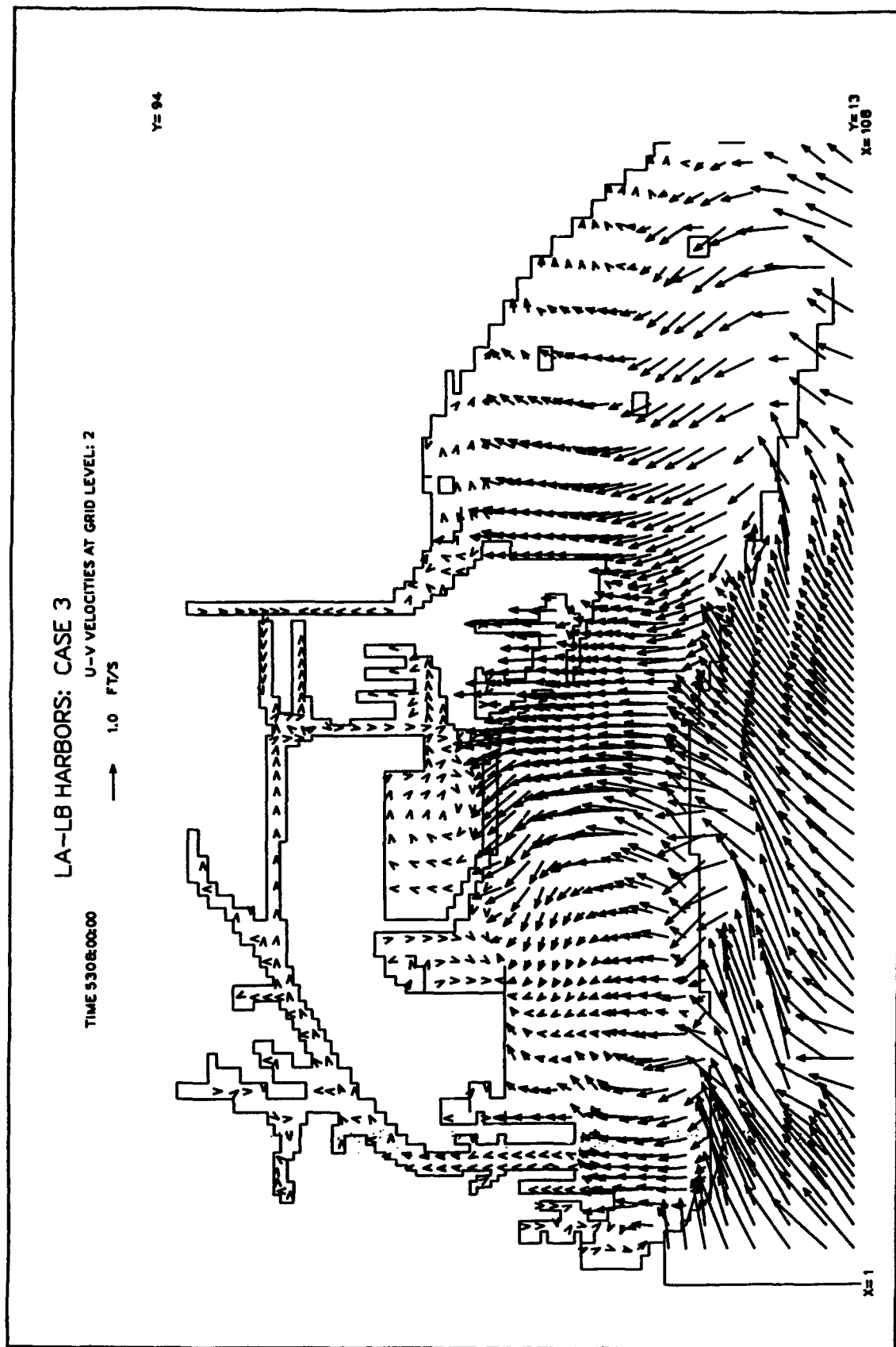
→ 1.0 FT/S

TIME 5296:00:00

Y= 04







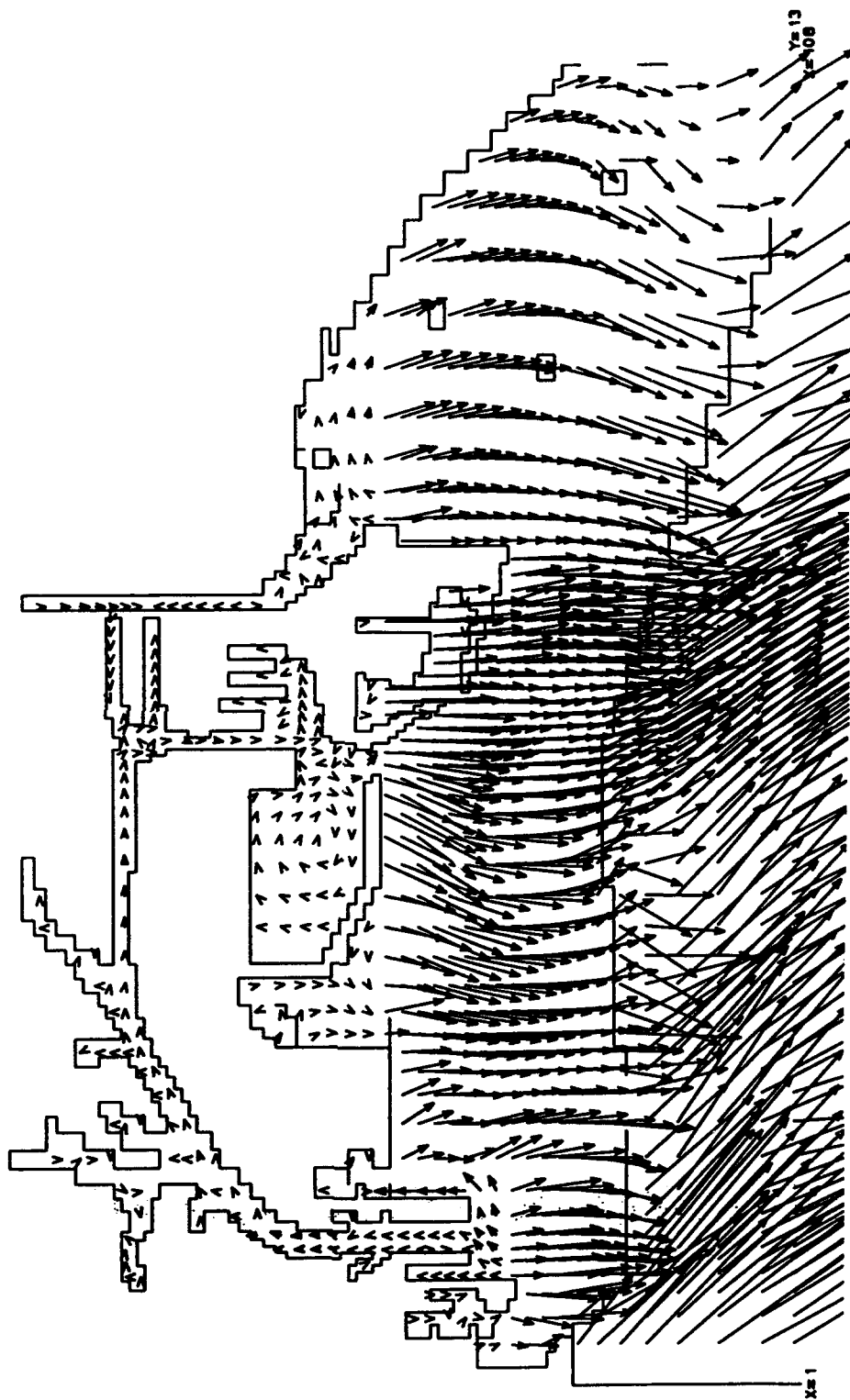
LA-LB HARBORS: CASE 3

U-V VELOCITIES AT GRID LEVEL: 3

TIME 5308:00:00

→ 1.0 FT/S

Y= 94

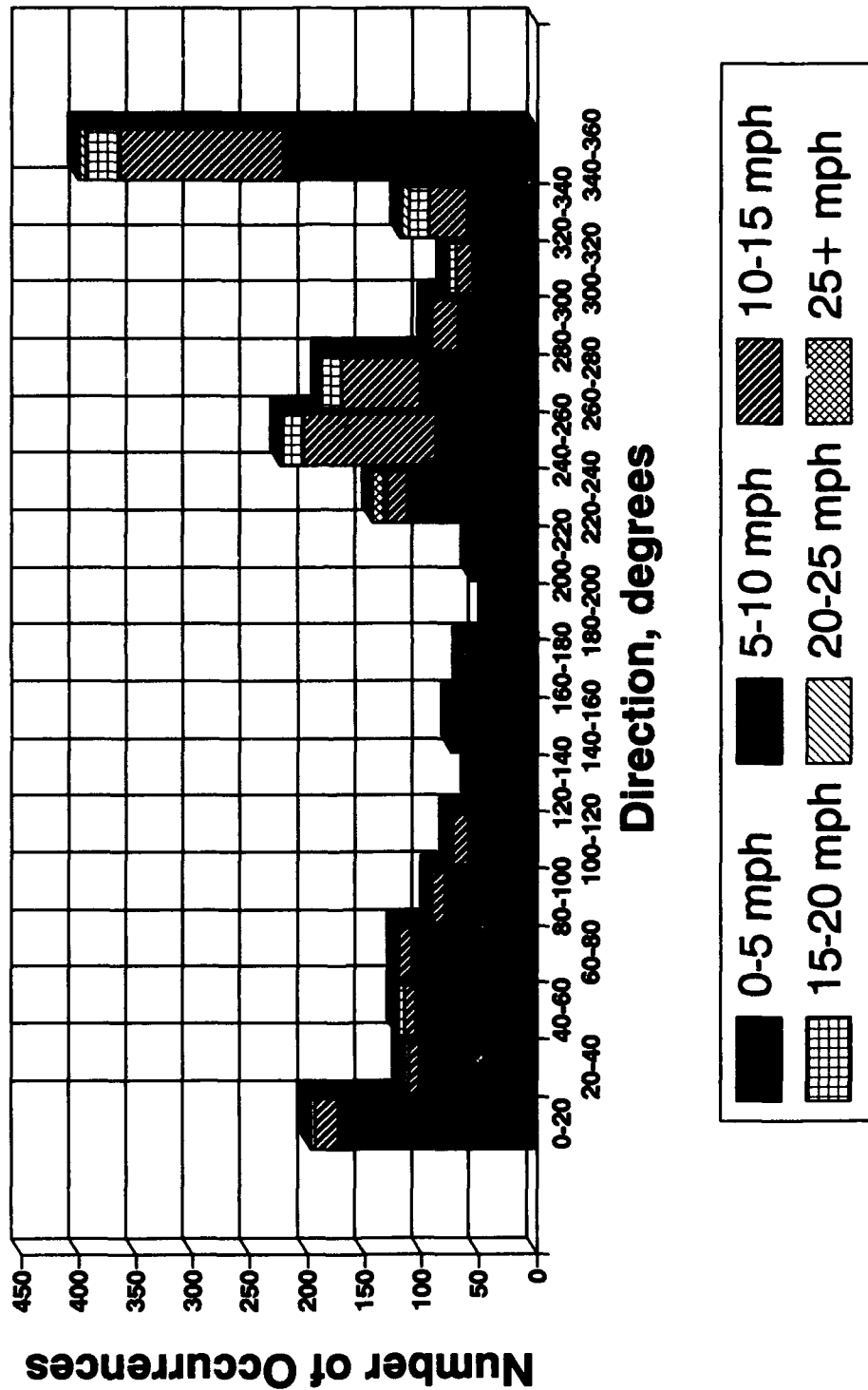


Appendix A

Winds on San Pedro Breakwater

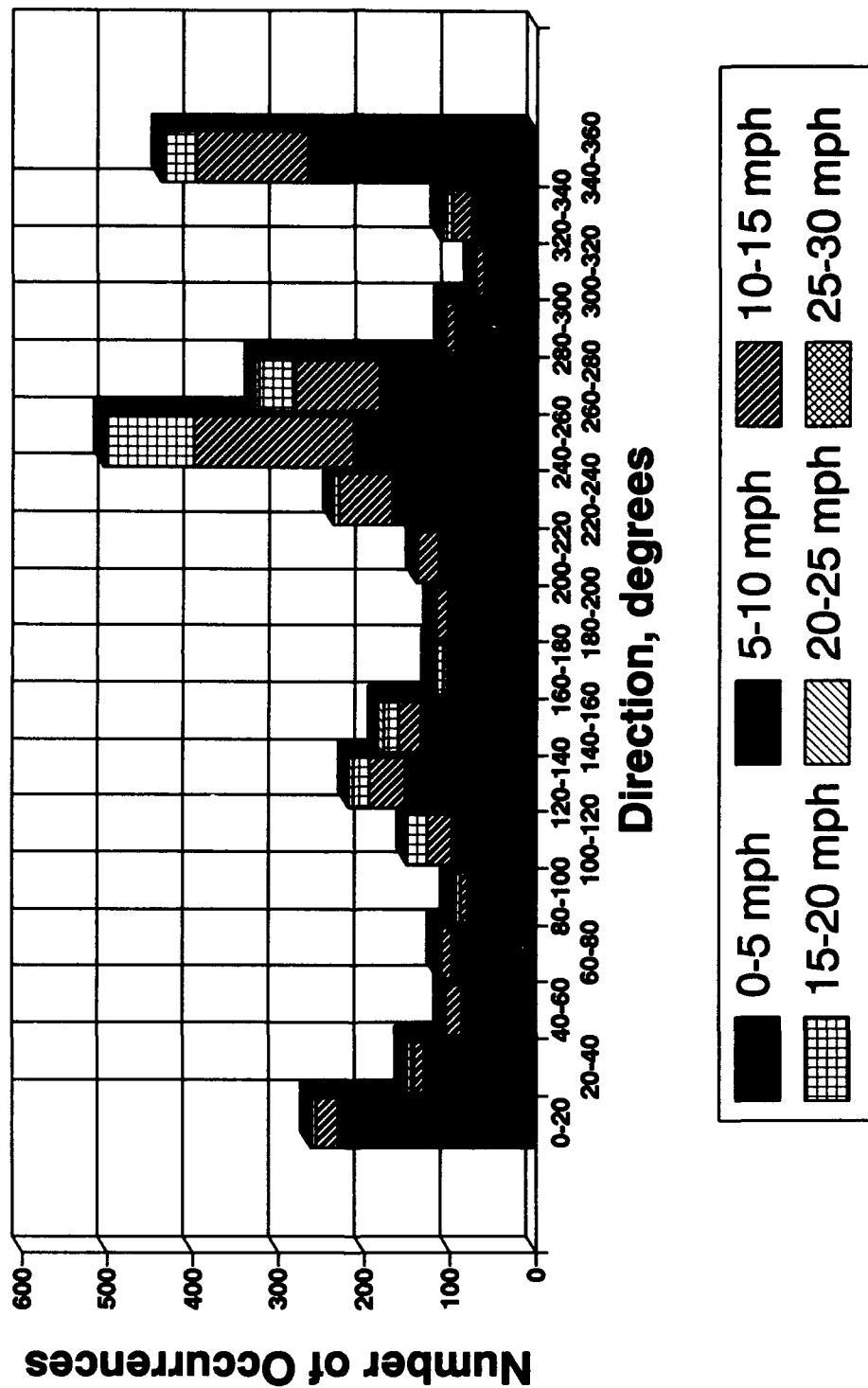
Winds On San Pedro Breakwater January 85 88

Note: Total Number of Occurrences = 2314



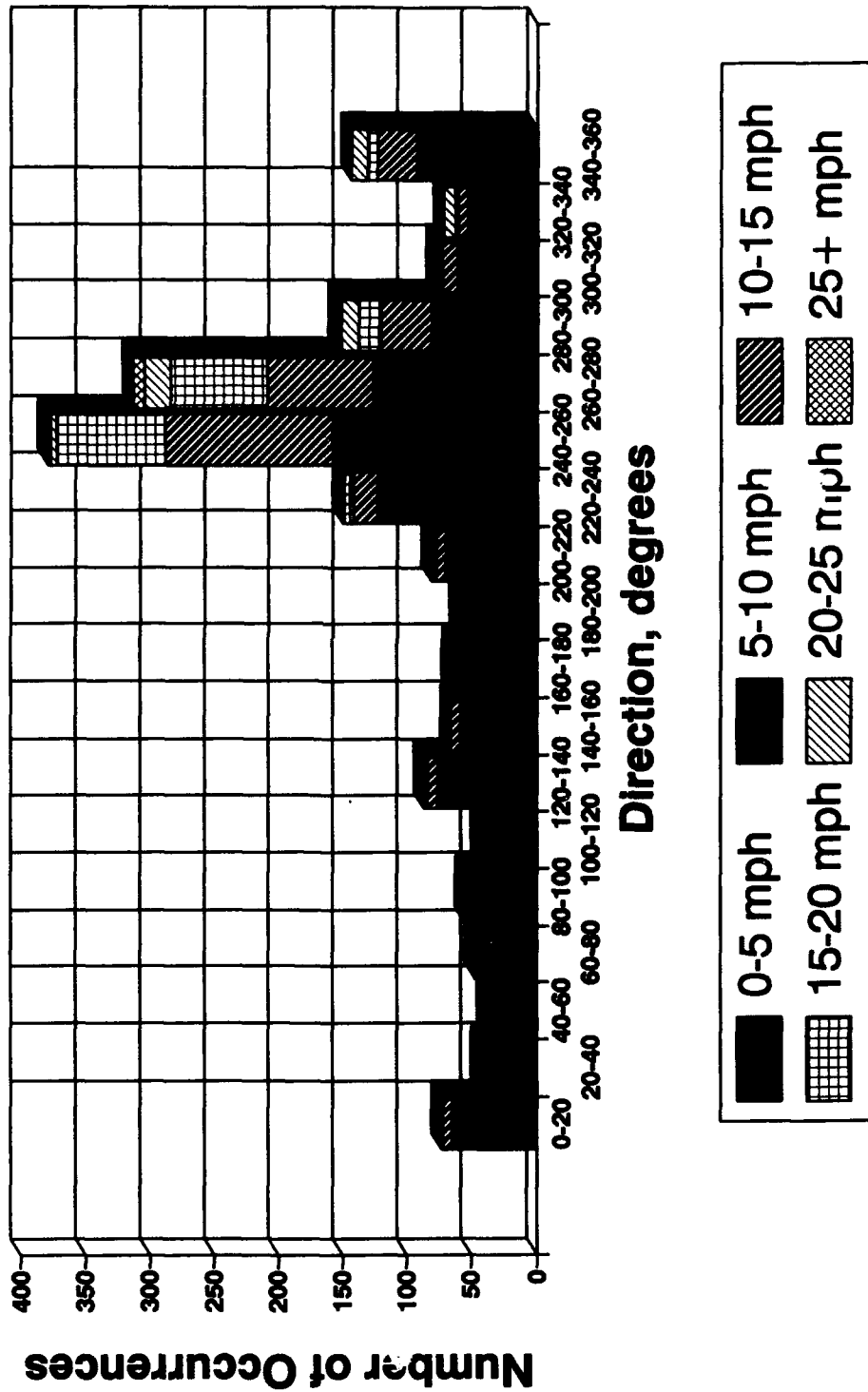
Winds On San Pedro Breakwater February 85 86 88

Note: Total Number of Occurrences = 3528



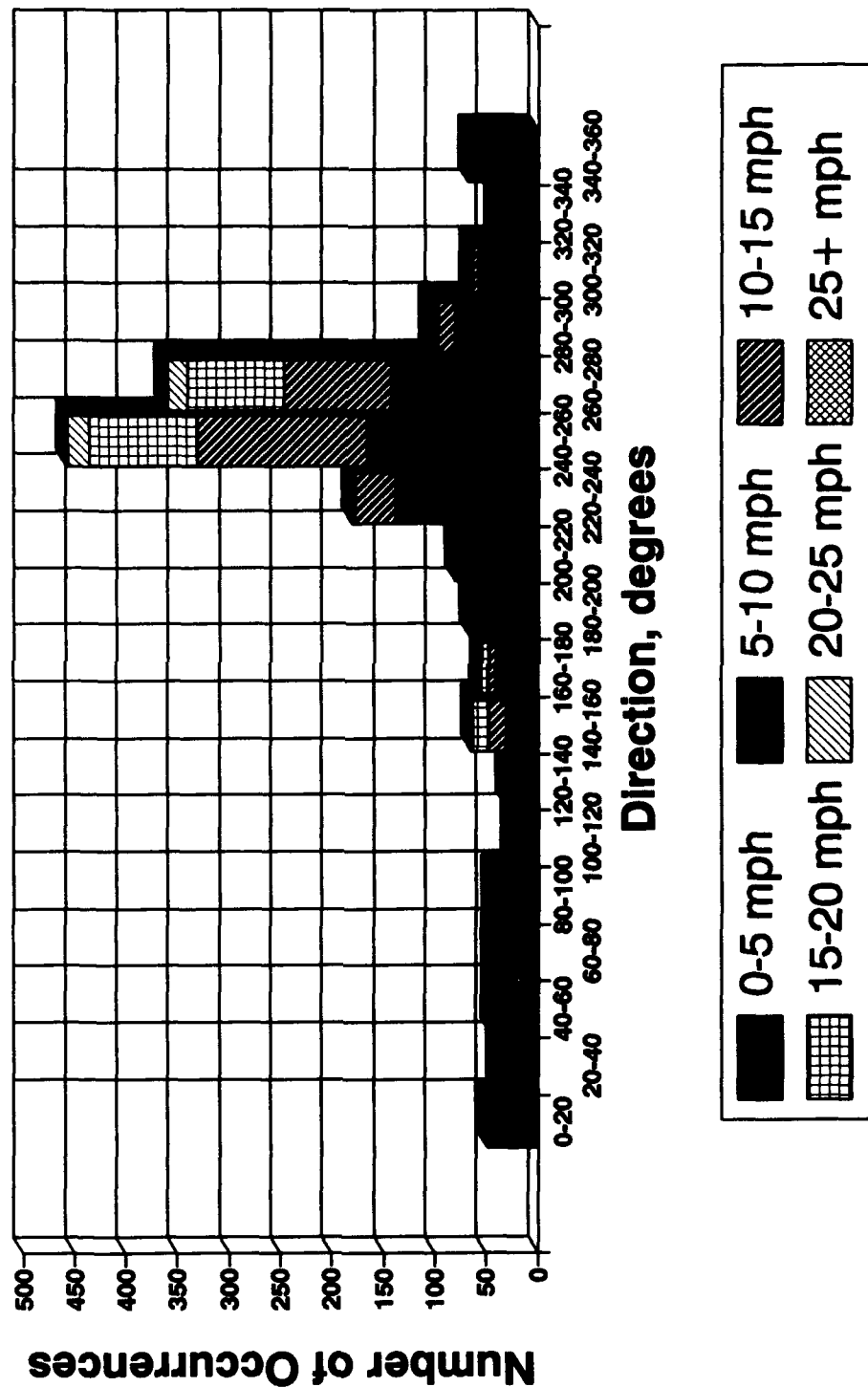
Winds On San Pedro Breakwater March 85 86 88

Note: Total Number of Occurrences = 1988



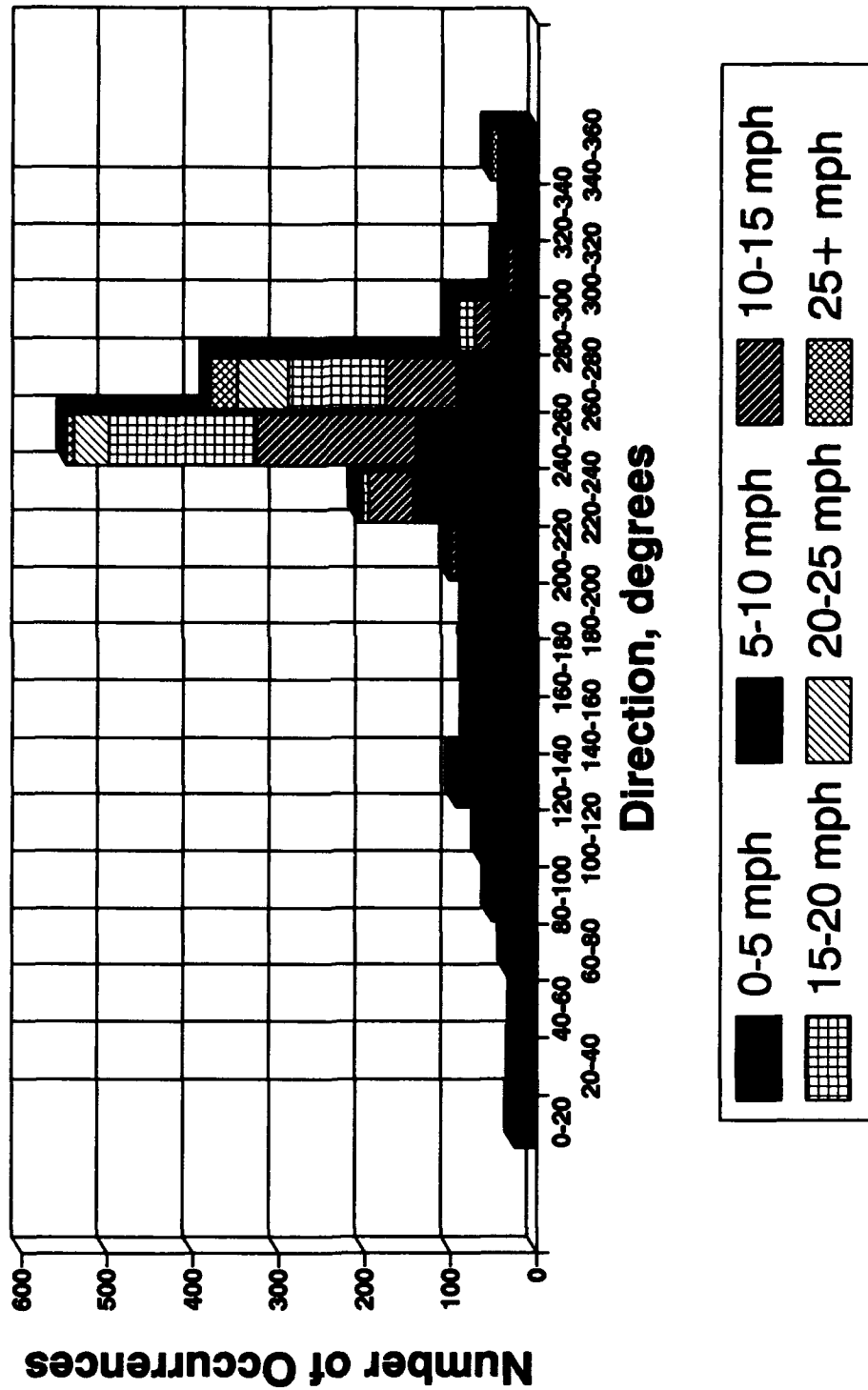
Winds On San Pedro Breakwater April 86 88

Note: Total Number of Occurrences = 1875



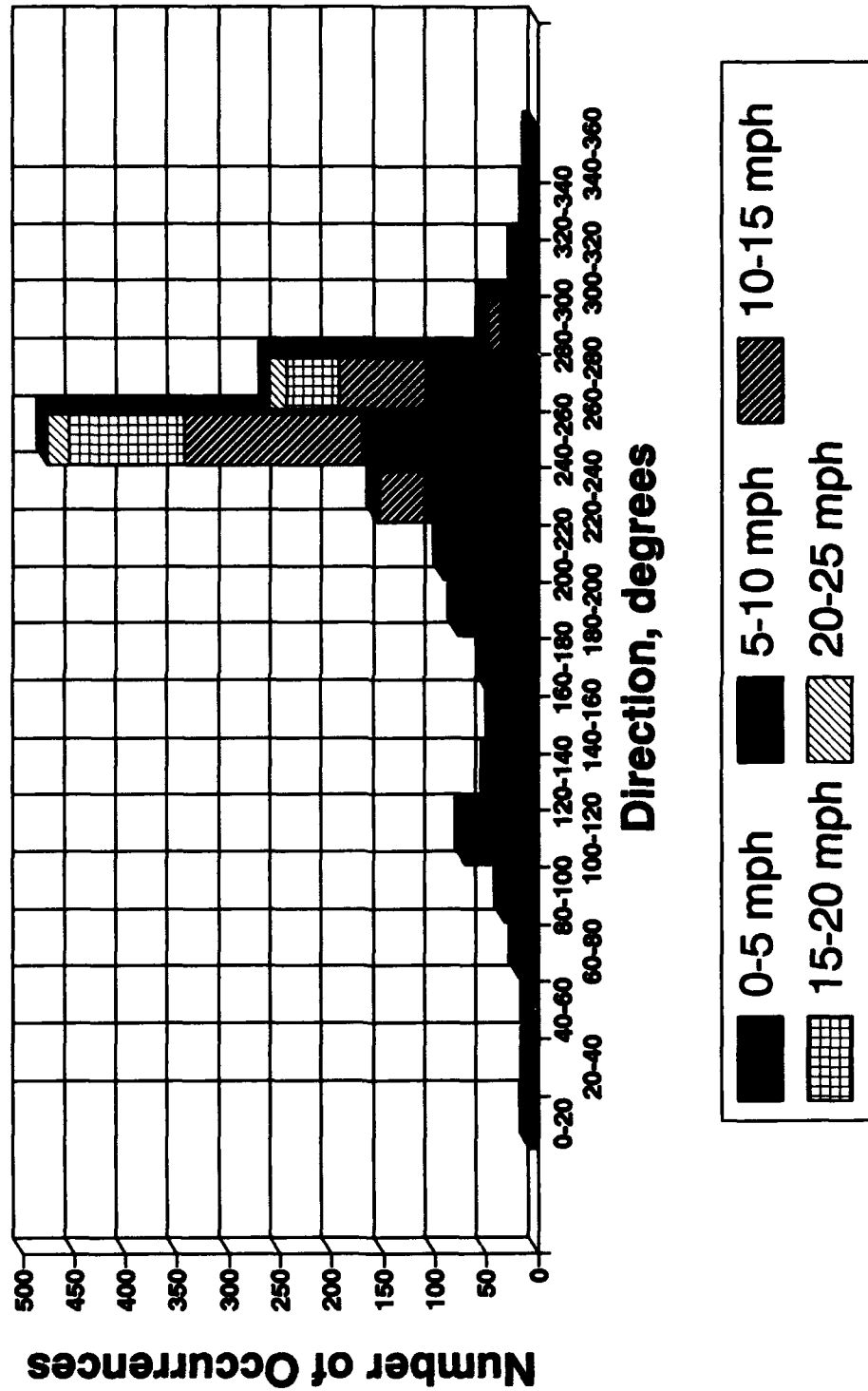
Winds On San Pedro Breakwater May 86 88

Note: Total Number of Occurrences = 2048



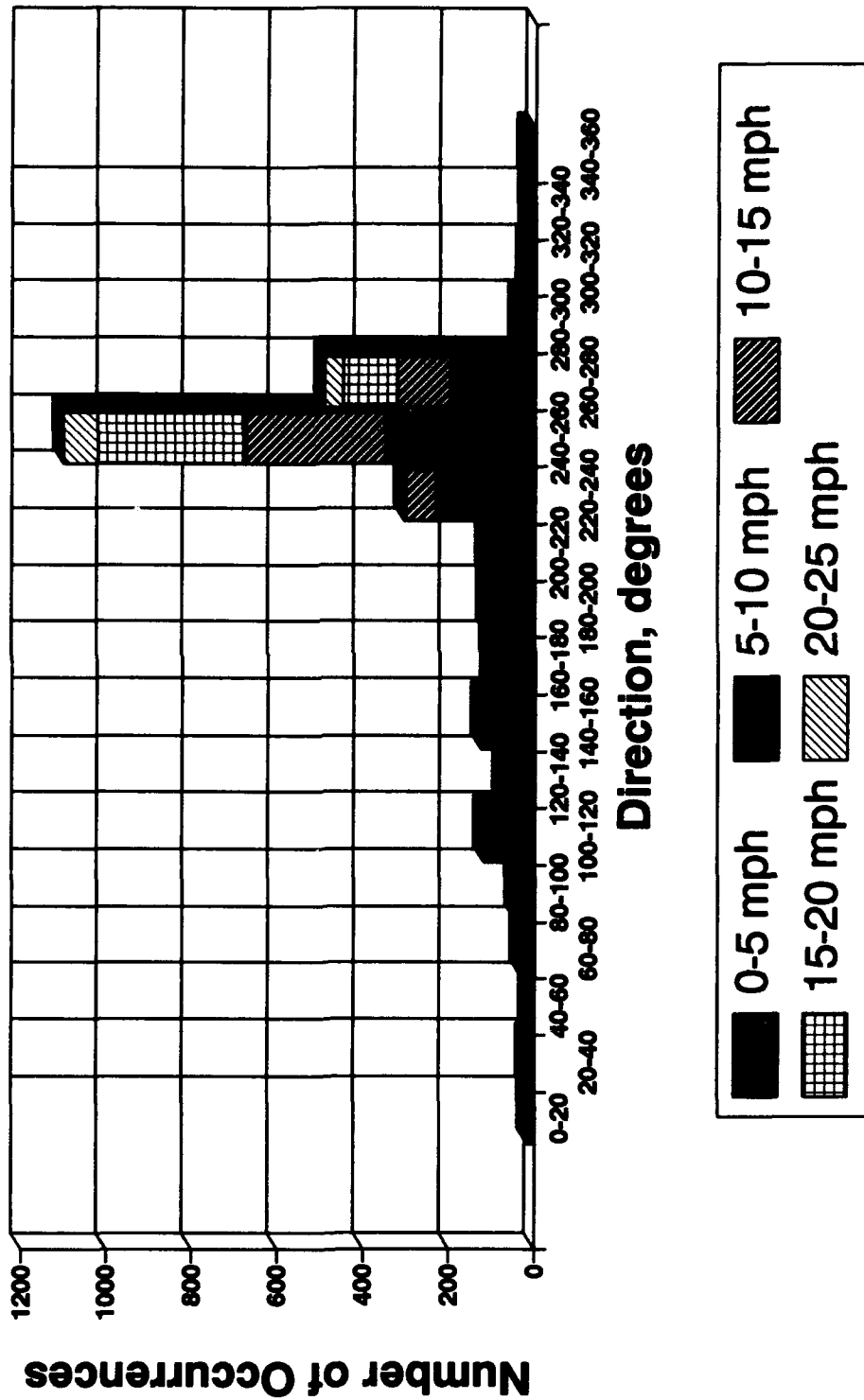
Winds On San Pedro Breakwater June 1988

Note: Total Number of Occurrences = 1438



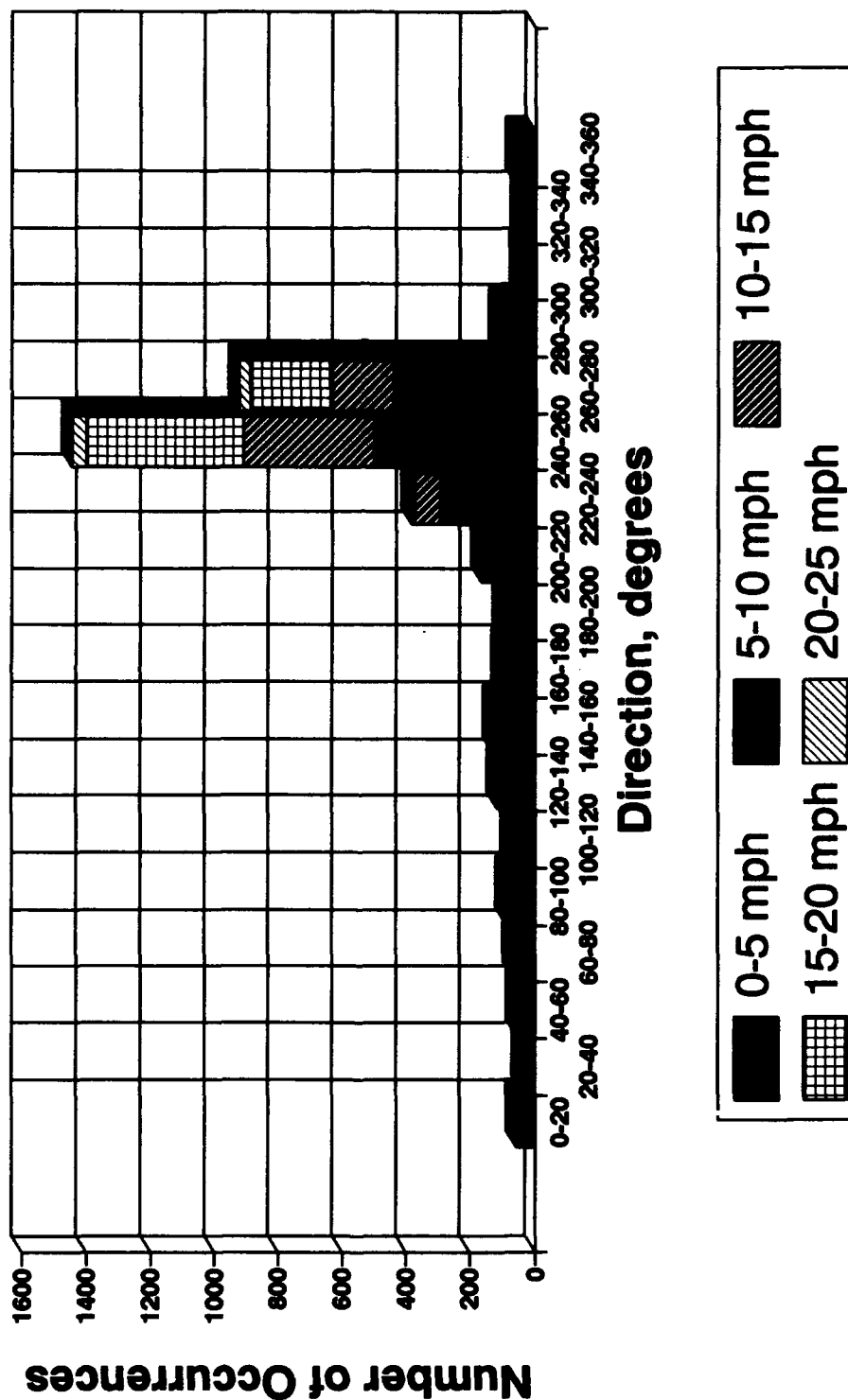
Winds On San Pedro Breakwater **July 84 85 88**

Note : Total Number of Occurrences = 2789



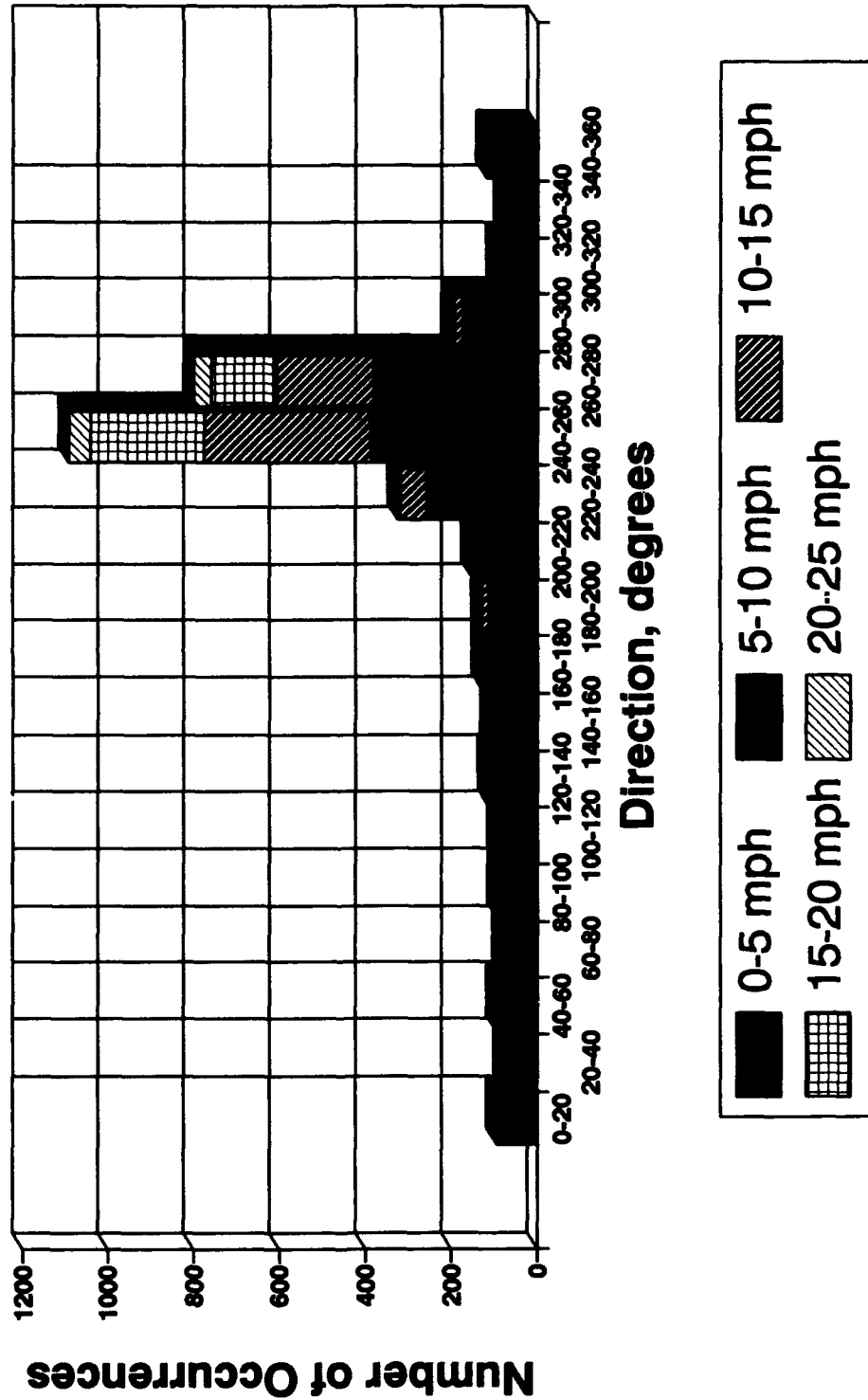
Winds On San Pedro Breakwater August 84 85 88

Note: Total Number of Occurrences = 4094



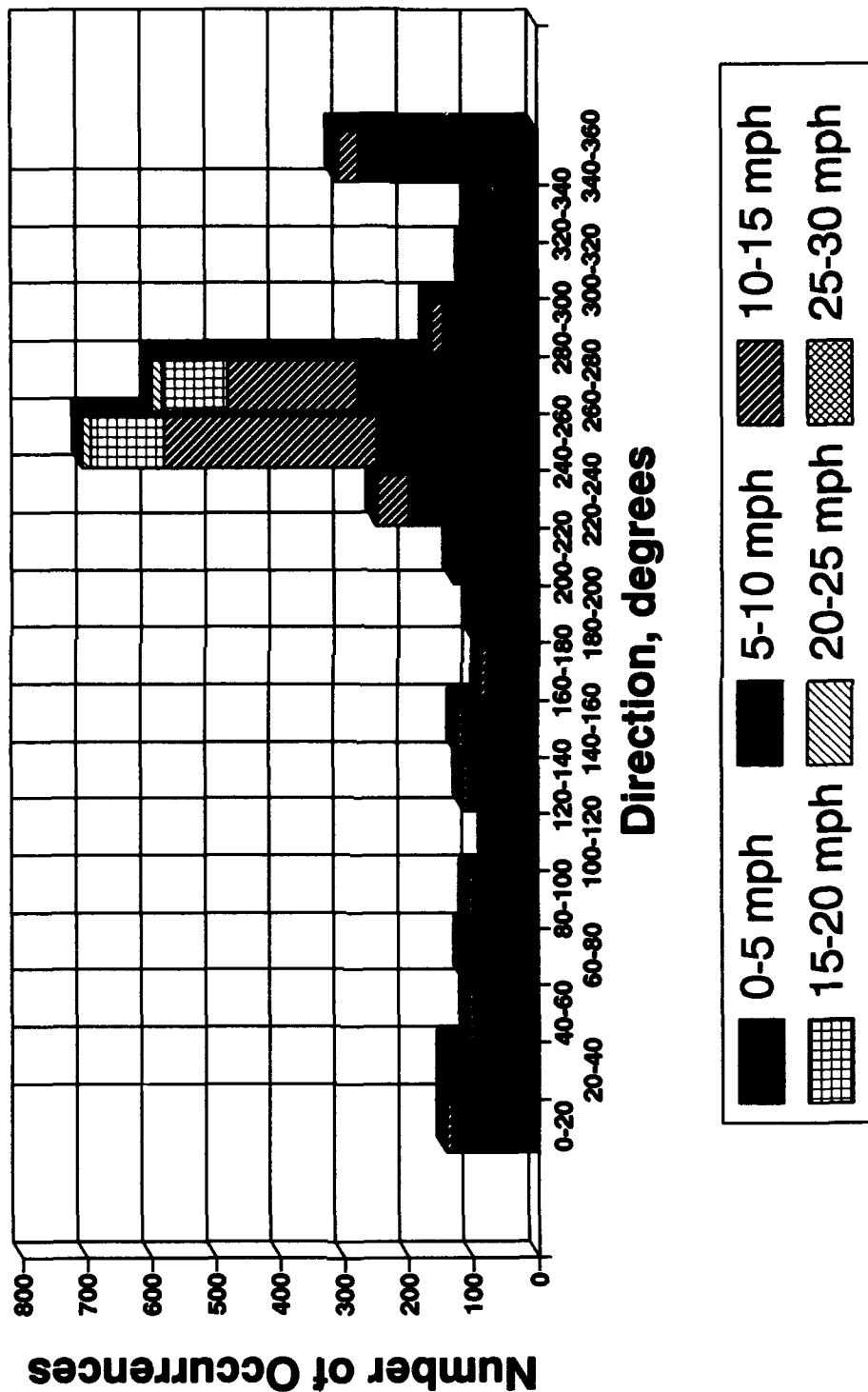
Winds On San Pedro Breakwater September 84 85 88

Note: Total Number of Occurrences = 3906



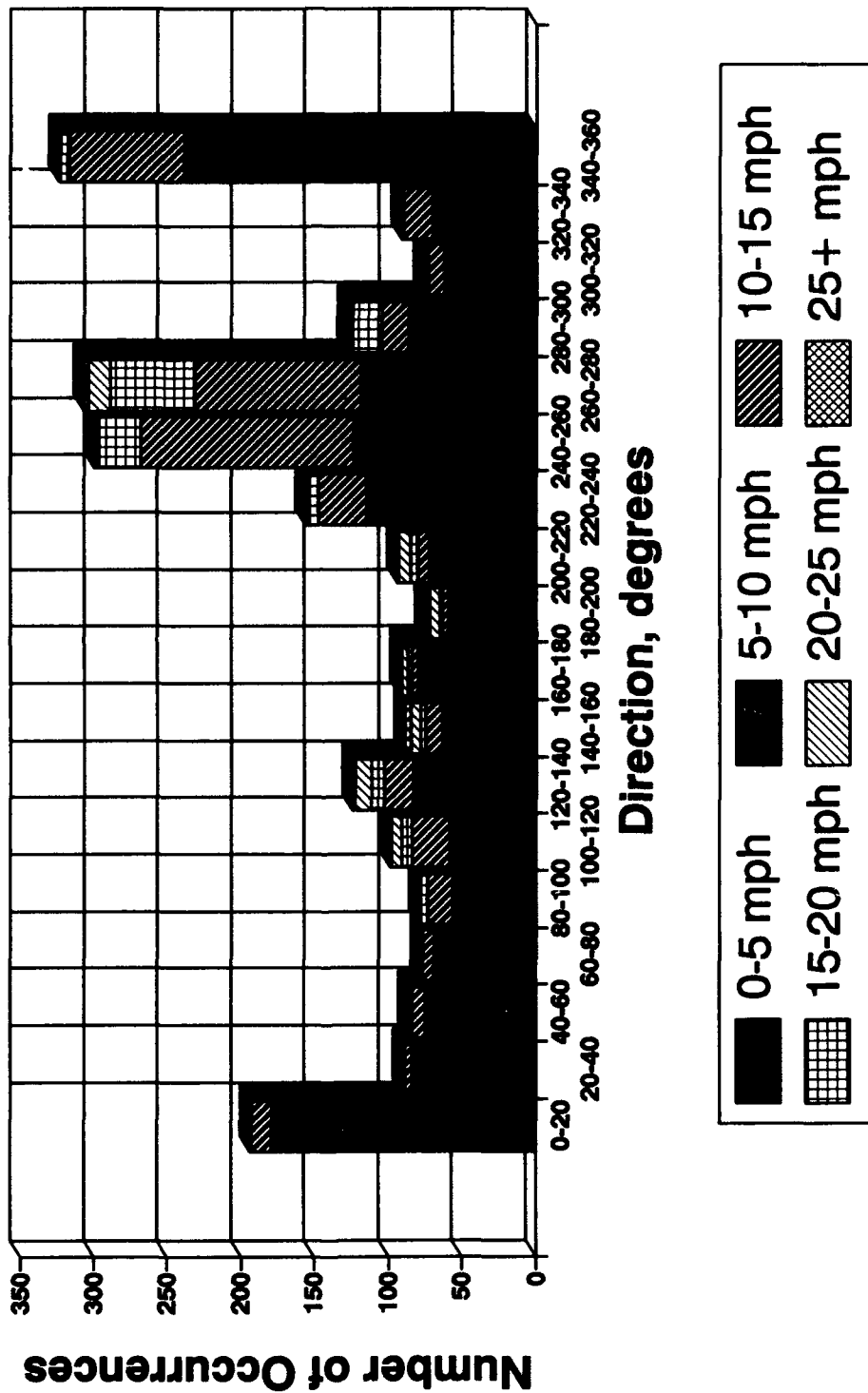
Winds On San Pedro Breakwater October 84 85 87

Note: Total Number of Occurrences = 3550



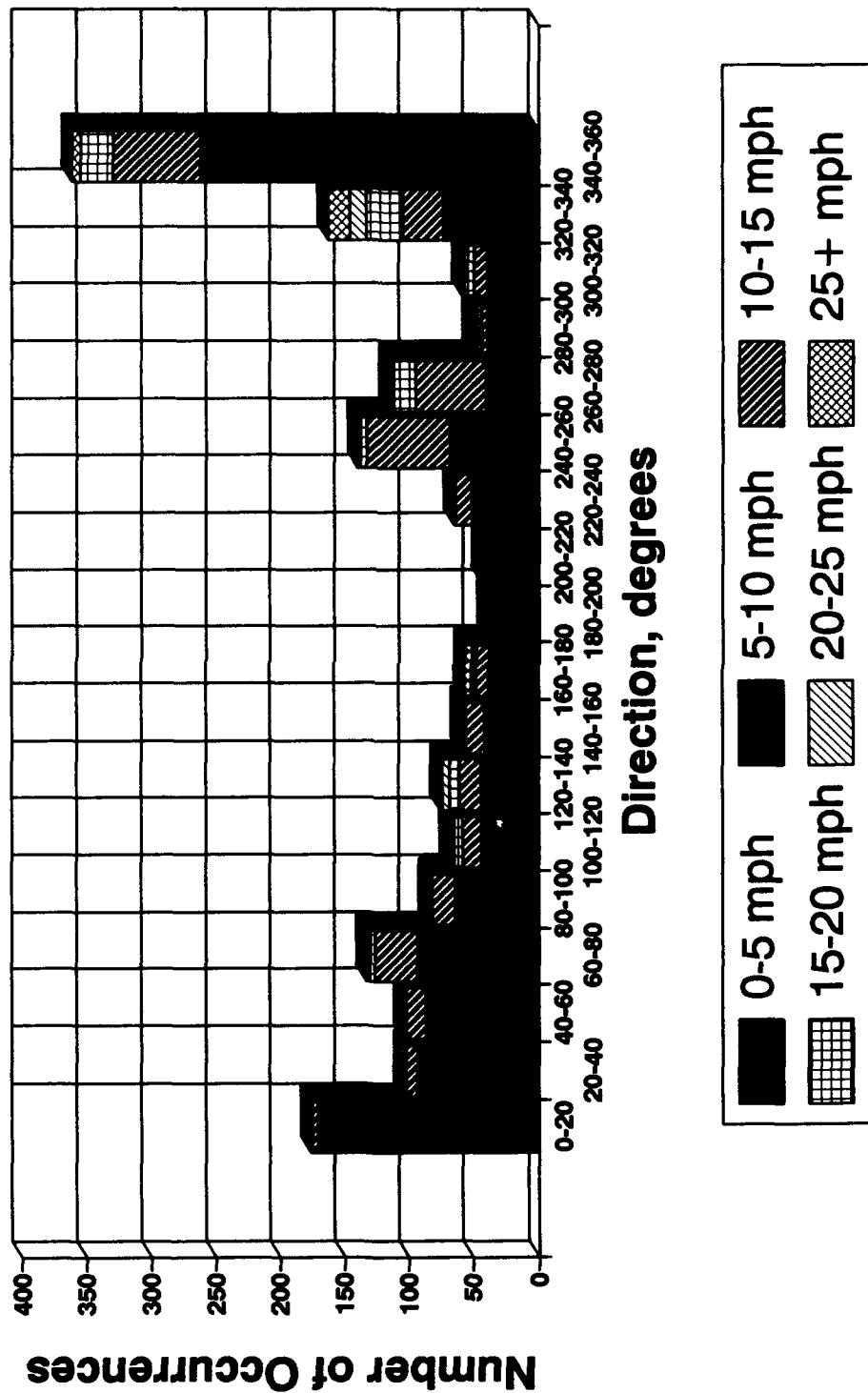
Winds On San Pedro Breakwater November 84 85 87

Note: Total Number of Occurrences = 2489



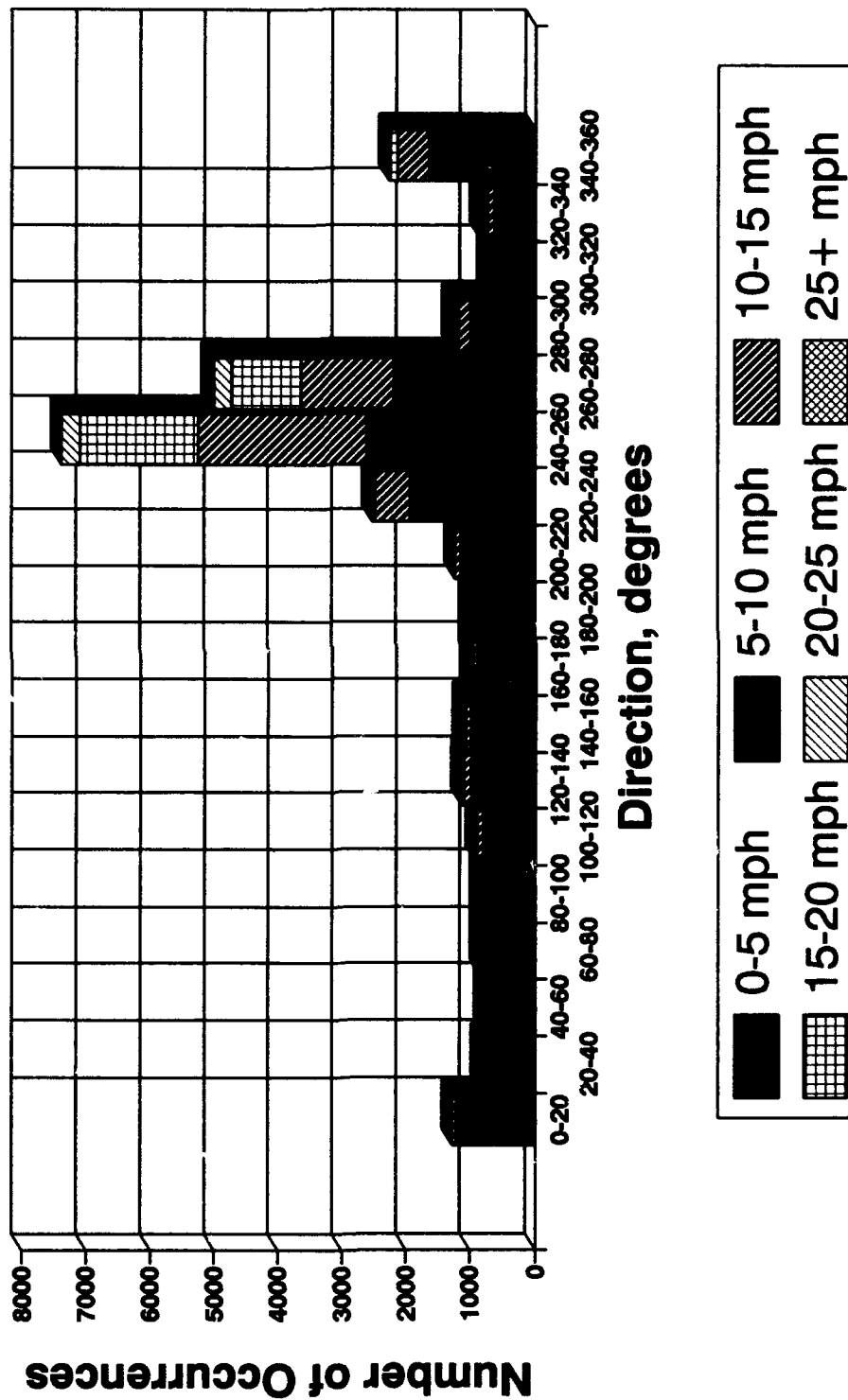
Winds On San Pedro Breakwater December 84 85

Note: Total Number of Occurrences = 1935



Winds On San Pedro Breakwater Cumulative Years 1984-1988

Note: Total Number of Occurrences = 31954



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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE April 1994		3. REPORT TYPE AND DATES COVERED Final report
4. TITLE AND SUBTITLE Los Angeles and Long Beach Harbors, Model Enhancement Program, Effects of Wind on Circulation in Los Angeles-Long Beach Harbors			5. FUNDING NUMBERS	
6. AUTHOR(S) William C. Seabergh, S. Rao Vemulakonda, Lucia W. Chou, David J. Mark				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Engineer Waterways Experiment Station 3909 Halls Ferry Road, Vicksburg, MS 39180-6199			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) See reverse.			10. SPONSORING/MONITORING AGENCY REPORT NUMBER Technical Report CERC-94-7	
11. SUPPLEMENTARY NOTES Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) A previously calibrated numerical three-dimensional hydrodynamic model for Los Angeles-Long Beach Harbors, California, was applied to study the combined effects of tide and wind on circulation. The model was calibrated and verified successfully with field data for a summer wind condition. In this report the calibration is compared to a no-wind condition to understand the effects of typical wind conditions on circulation. Also, wind conditions for approaching (winds from the southeast) and passing (winds from the north) frontal systems, typical of fall-winter weather patterns, were simulated. Results indicated the effects of wind can be significant.				
14. SUBJECT TERMS Harbors Long Beach Harbor Wind-driven circulation Hydrodynamics Numerical models Los Angeles Harbor Tidal circulation			15. NUMBER OF PAGES 217	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT	

9. (Concluded).

U.S. Army Engineer District, Los Angeles, Los Angeles, CA 90053-2325;

Port of Los Angeles, San Pedro, CA 90733-0151;

Port of Long Beach, Long Beach, CA 90801-0570